1OF1 RESEARCH

If a Tree Falls in the Woods

Does it make a sound? A study of how trees produce sound, how it travels, and what evidence it leaves.

November 2026

Scientific monograph and computational companion

Contents

Abstract 2

1. The event and the proposition 3

2. Mechanics of collapse and the accounting of released energy 8

3. From compressible motion to acoustic radiation 13

4. The forest as a propagation experiment 19

5. Receivers, nervous systems, and the production of a sound 25

6. What can an unheard pressure field specify? 31

7. Dissipation, entropy, and the lifetime of a sound 36

8. Classical emergence and the spacetime location of production 40

9. The historical question and the logic of making a sound 43

10. Changing the conditions of production 49

11. A numerical experiment on what the tree produces 55

12. A prospective, unattended validation campaign 66

Mathematical appendix on certifying what the tree emitted 73

Can a finite pressure array miss a whole transient? 77

Glossary and formal ontology 79

Uncertainty and limitations register 81

Original contributions and prior art 82

Adversarial scientific review 83

Annotated literature and source records 95

Final verdict 104

Abstract

Does an unwitnessed falling tree make a sound? We treat production as a causal predicate of the collapse and distinguish radiated energy from receiver response, retained evidence and auditory experience. Conservation laws and exterior-wave uniqueness give sufficient conditions for positive radiation from an exposed moving boundary. Engineered volume sources, evacuation of the medium, slow-motion limits and finite receiver apertures delimit the result. A calibrated angular sampling argument shows when finitely many pressure histories determine emitted energy. Twelve directions recover energy exactly for a quadratic far-field pattern. A cubic mode invisible in those directions gives identical histories for synthetic sources differing tenfold in energy. A separate transient construction extends the null-space result to arbitrary finite point-pressure arrays in an ideal exterior. A soil- and atmosphere-coupled mechanical framework, a numerical hinge–contact model, forest propagation controls, detection experiments and bounds on waveform reconstruction distinguish physical emission from accessible evidence. The numerical yields and site maps are conditional simulations. Archival acoustic and seismic cases establish observational contact without supplying a universal radiation fraction. An unattended field protocol specifies independent event labels, calibration and controls. An ordinary treefall produces sound in the physical sense; the absence of a hearer removes the possibility of an evoked experience in that hearer.

1. The event and the proposition

An upright tree stands on a wooded slope. Its anchorage yields, its crown sweeps through neighboring branches, and its stem comes to rest on the ground. Suppose nobody is around to hear it. **Does it make a sound?** The grammatical subject is the tree. The verb assigns production to that subject. The absence of someone nearby specifies a circumstance of production. An adequate investigation must identify the product, determine whether and where it exists, and establish what can be attributed to this tree as distinct from the wind that brought it down.

There is observational contact with the physical phenomenon. The US National Park Service catalogued a tree-fall recording during its July 2009 Rainbow Loop deployment and presents a time–frequency display [R1]. Stanford's Jasper Ridge Biological Preserve reproduced a seismogram associated with the July 1995 fall of a large eucalyptus in Woodside [R2]. These are different trees and different channels. Their combination supplies neither joint calibration nor an airborne-to-ground energy ratio. In the 2018 Quinault blowdown, surface damage and a nearby seismometer helped reconstruct a short-lived wind event. The authors describe the attribution of individual seismic impulses to large falling trees as likely [R3]. That qualification matters whenever wind can independently drive both a tree and a sensor. An inventory of detected events is evidence for existence. A census of acoustic efficiency would require representative falls and a much fuller measurement design.

The Acoustical Society of America recognizes a physical sense involving oscillations propagated through a supporting medium and a sensory sense in which such oscillations evoke an auditory sensation [R5]. On the physical definition, ordinary air-coupled collapse makes sound. Exposed surfaces displace and load their surroundings. The explanation has testable content beyond the choice of words. It predicts an outgoing component for specified boundary motions, admits a counterexample when the medium is removed and places limits on what a finite array can establish. The following argument asks what changes when one replaces ordinary conditions by the universal quantifier "every possible fall."

Thirteen terms and their scientific commitments

Expression	Formal role	Question resolved by specifying it
If	Restriction of histories or intervention	Actual token, generic case, causal intervention, or universal law?
A	Selection or quantification	One token, an ensemble draw, or every member of a class?
Tree	Extended material individual	Do the root plate, entrained soil and detached branches belong to the source?

Expression	Formal role	Question resolved by specifying it
Falls	Transition on a time interval	Does onset, fracture, partial collapse or final contact define the event?
In	Spatial relation	Is the source, receiver, propagation path or entire support inside the forest?
The woods	Material and ecological environment	Which ground, vegetation, weather, boundaries and background processes apply?
Nobody	Quantification over eligible subjects	Are humans alone absent, or all subjects capable of auditory experience?
Is around	Spatial and temporal neighborhood	A fixed radius, a causal reach before a deadline, or an audibility footprint?
To hear	Capacity, opportunity or realization	What distinguishes an available ear, sensory transduction and a conscious percept?
It	Event identity and attribution	Which disturbance came from this fall among other contemporary causes?
Does	Tense and truth evaluation	Habitual production, this event or a law over possible events?
It make	Causal production	Does downstream impact or a neighboring trunk count as a source attributable to the fall?
A sound	Choice and individuation of product	Local mechanical event, wave, disposition, record or evoked sensation?

An individual fall admits an existential proposition; a physical law quantifies over an entire class of histories. A population probability requires a measure over that class. Ordinary language often asks for a generic statement, expressing what happens under ordinary conditions without stipulating a measured prevalence. One authenticated trace can establish that some treefalls generate detectable waves. It cannot establish that all falls do so, or attach a confidence interval to a population sampled only when loud events triggered a recorder. A law for exposed moving surfaces in freely radiating air does something else again. It licenses a conclusion for a specified mathematical class without counting samples from that class.

The two pronouns in the full question have different customary referents. The thing someone could hear can be a fall or one of its sounds. The thing doing the making is usually the tree. Treating these referents as interchangeable effectively assumes that the product already exists in the precise form distinguished by a listener. It is more informative to allow the same mechanical event to generate multiple physical products and ask

what each product requires. The singular article likewise poses no counting problem if it means at least one sound. Counting branches, individual pressure transients, echoes, or whole crashes is a separate segmentation task. A detector trained on isolated snaps can overcount a tree by detecting several entirely genuine acoustic events during a single collapse.

Sources and contrasts

Let e denote an episode with source region K and time interval J. Let b denote weather, ground, other active sources and initial conditions. In linear acoustics, one can excite the tree channel and solve for the retarded contribution p_e, keeping other inputs fixed. In a turbulent, nonlinear system this clean decomposition is a modeling decision. Restraining a tree can change wind work, aerodynamic blockage, soil motion and the behavior of neighboring stems. A paired calculation therefore estimates the effect of *the specified intervention*. For a single historic storm there need be no uniquely known baseline pressure history to subtract from the measured one.

Even linear superposition does not give additivity of squared pressure. If the background is b and the event contribution at a receiver is s, the change in time-integrated squared pressure is $\|s\|^2 + 2\langle b, s\rangle$. Destructive interference can make the change negative. Comparing a recorder's displayed power in neighboring windows is therefore different from calculating the energy of an isolated emitted field. The expected cross term vanishes under particular background independence and zero-mean assumptions. Neither condition follows from the sound of wind and a tree falling in that very wind. A negative power contrast in a window does not imply that the tree absorbed every wave it made.

Define $G_m(e)$ as an attributable propagated disturbance in medium m. Let $E_{B,S}(e)$ denote the event's outgoing energy in band B through accounting surface S with a stated outward-wave convention. For receiver o, keep separate the predicates P_o (present), D_o (successful event detection under a rule), R_o (retained record) and H_o (a conscious auditory percept caused by the event). A mechanical response, neural response and report likewise have separate identifiers. Each predicate has a time argument. A person can play a recording after every original airborne wave is operationally inaccessible. The later pressure field comes from a loudspeaker, and the later experience has a causal link to the tree through the stored record. Neither is a percept at the time of collapse.

Attribution is causal. Suppose thunder causes a vulnerable tree to fail. A recorder can capture the thunder very clearly while its passband rejects the fall. That record may increase the conditional probability of a fall. It still need contain no measurement of pressure generated by the fall. Conversely a falling tree can excite an adjacent trunk that radiates most of the acoustic energy. The fall is a cause of this radiation, while the neighboring trunk is the surface doing work on the air. Event attribution and the location of an equivalent radiator answer different experimental questions. A forester locating damage and an acoustician mapping a radiator can assign different coordinates without either committing an error.

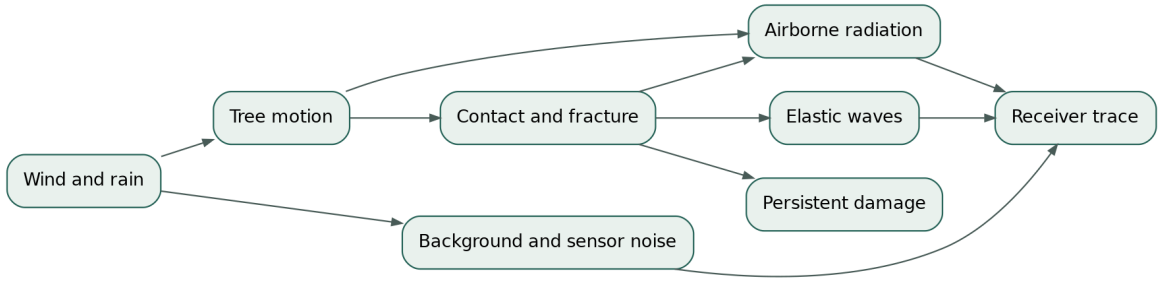

Figure 1: Causal routes from weather and tree motion to environmental evidence. A receiver trace may have several causes.

Four different reports of silence

Physical silence in an emission study means that a specified source component vanishes over a surface, band and interval. A channel null means that a receiver couples to none of that component even with noiseless readout. Decision silence means that a test failed to register a detection at a declared operating point. Phenomenal silence means that a specified population experienced no auditory sensation caused by the event. Each can hold while another fails. An angular node, a filter outside the band, a missed detection and the absence of a subject give different reasons for a sparse dataset.

A fifth situation is particularly easy to mishandle. When no microphone is present, there is no test outcome. Recording this situation as a failure of detection biases estimated performance. When no usable evidence is retained, the historical question may be undecidable for a later investigator even if every admissible history has a definite pressure field. “Unknown” describes the investigator’s inference. It is not an additional solution value of the wave equation. An experimental design should represent missingness, below-threshold observations and verified zeros as three different data states.

Observer independence as a causal statement

Hold the physical initial and boundary states in the causal past of the emitter fixed. Change whether a later physical state is designated as a record and whether anyone later interprets that state. A well-posed classical initial-boundary value problem gives the same emitted field in the two descriptions. Removing the designation “observer” does no work on the air. Removing a microphone diaphragm, an absorbing body or an animal leaning on a bent branch can change the load and thereby the physical solution. The independence claim concerns the necessity of observation as such. It does not require all equipment and organisms to be acoustically transparent.

One can approximate a relevant pair of interventions while leaving a microphone physically in place. In one configuration its output is written to a remote store. In a second the signal meets an equivalent electrical and mechanical load but is discarded. When the loads match, the same pressure history acts on the diaphragm irrespective of record retention. If changing the electronics changes the load, a reference-source calibration

can measure how good the approximation is. The trial tests sensitivity to retention under matched physical conditions. It does not establish by direct observation that no interaction with anything occurred. The Earth, root plate and air already interact before instrumentation enters the argument.

An emitted wave can exist before it reaches a distant microphone. It can pass through a place where a detector might have stood. A person listening to a live transmission originating near the tree could even experience a reproduction before the direct airborne disturbance arrives at their own location. Each narrative requires an event time, a propagation route, a condition for detection and a referent for “that sound.” A physically local statement about the origin remains available throughout.

Reading the evidence

This investigation uses several kinds of warrant. A park’s archive records a custodian’s attribution. A conservation identity follows from its constitutive and boundary assumptions. Numerical convergence checks that a discretized problem is being solved consistently. A synthetic inference experiment determines what is identifiable in a stated statistical model. None of these establishes a universal percentage of gravitational energy radiated by all forest trees. Evidence about calibration, admissible source patterns and ecological variation must enter separately.

The distinction leads to a productive quantitative question: under which assumptions could an array certify the amount of energy the tree made? For a specified angular basis, the answer depends on singular values of a measurement operator. For an unrestricted basis, even noiseless arbitrarily long records from finitely many directions may leave a whole radiation pattern unseen. This limitation arises before any question of human consciousness. It also suggests a field strategy: establish a positive attributable signal where possible, and distinguish that evidence of existence from the substantially more demanding estimate of total source energy.

2. Mechanics of collapse and the accounting of released energy

What the fallen trunk can establish

Consider the same tree immediately before and immediately after a storm. A survey might reconstruct its mass, center-of-mass displacement, and final orientation almost exactly. It could constrain the gravitational work accurately even if every microphone had failed. These observations would put much weaker constraints on the acoustic field. A rigid tree pivoting against a root plate, a trunk buckling into a neighboring crown, and a trunk descending on an eroding bank can reach approximately the same final position with different contact times and terminal speeds. The historical fall is a path through mechanical states. The final state supplies one integral of that path.

Take a material tree, including explicitly designated attached roots and branches, in locally uniform gravity. A marked piece of wood that separates from the trunk and leaves the observation region carries energy with it. With positive downward release, the gravitational contribution of the chosen material is

$$W_g = \int_{B_0} \rho_{w0}(X) g [z(X,0) - z(X,T)] \, dV_0 = Mg[z_{\mathrm{cm}}(0) - z_{\mathrm{cm}}(T)].$$

The second expression presupposes fixed membership and mass. If the root plate is included, its rise offsets part of the crown's descent. If it is excluded, forces at the root interface do work across the tree boundary. The same piece of soil cannot be both part of the moving system and an external loss. Sap and detached wet foliage create smaller, conceptually identical bookkeeping choices. Gravitational work follows vertical displacement of the mass, even when each material point follows a complicated curved path.

Initial standing equilibrium is a local balance of force and moment against the support. A tree can already store elastic energy under wind loading or against a neighboring crown. Such preparation changes the energy available when the constraint releases. A perfectly vertical rigid rod hinged at a frictionless base, given exactly zero tilt and zero velocity, remains stationary under the equations for all time. A finite displacement, a nonzero initial velocity, a torque, or instability plus disturbance must initiate motion. Thus conditioning on a successful fall does not determine the initial angle, the wind field, the energy available, or a probability distribution over causes.

Fixed-axis rotation and root failure

Let a be the distance from hinge to center of mass and I the moment of inertia about a horizontal hinge. Let θ increase from the upward vertical. For a fixed pivot and approximately rigid tree,

$$I\ddot{\theta} = Mga \sin\theta + M_{\mathrm{wind}} - M_{\mathrm{root}} - M_{\mathrm{other}}, \qquad K = \tfrac{1}{2} I \dot{\theta}^2.$$

Moments are signed in this convention. A gust can accelerate or retard the tree. A cohesive root can store work during extension and return some during unloading. Multiplying by angular displacement gives the work–energy identity. With no other moments and rest at θ_0, the angular speed obeys $\dot{\theta}^2 = 2Mga(\cos\theta_0 - \cos\theta)/I$. The falling time is the integral of the reciprocal square root from θ_0 to the contact angle. The integrable endpoint singularity for $\theta_0 > 0$ matters in numerical quadrature. As θ_0 tends to zero, the time diverges logarithmically: the initial linearized equation has an exponentially growing mode whose amplitude is proportional to the release tilt. A numerical calculation initialized exactly vertically without a perturbation should never fall. Numerical roundoff breaking a symmetry cannot validate a physical trigger.

For a uniform slender rod of length L, the center of mass is at $L/2$ and $I = ML^2/3$. At first horizontal contact from a small release angle the limiting tip speed is $\sqrt{3gL}$. With $L = 20$ m and $g = 9.81$ m s^{-2}, it is 24.3 m s^{-1} if losses are absent. At the stipulated sound speed of 343 m s^{-1} this gives a tip Mach number near 0.071. This illustrative calculation supports a low-Mach description of gross motion in that example. It supplies no crack speed, decay rate or acoustic conversion factor. A broad crown can strike before the centerline reaches the horizontal. A sloping surface, elevated fork or breaking trunk can change both the contact time and the order in which different parts hit.

Represent root anchorage by a restoring moment $M_r(\theta, \dot{\theta}, h)$ with internal variables h recording soil yield, prior damage and irrecoverable rotation. Around a quasi-static operating point the derivative of resisting moment competes with $Mga\cos\theta$ and the slope of the applied moment. Positive effective tangent stiffness restores a displacement under dead loading. A negative tangent signals local instability in this one-coordinate model. Displacement-controlled and load-controlled trials need not traverse the same post-peak path. Neither peak moment nor initial stiffness determines the work integral. In winching experiments on Sitka spruce, Coutts distinguished soil resistance, root tension, root-plate weight and hinge bending. Earlier work used buried microphones to time root breakage. These observations support progressive rupture and give a way to distinguish stages. They do not measure the total airborne energy of a freely falling tree [M1, M2].

The root plate may migrate and heave. Writing $I(t)\ddot{\theta} = M$ for such motion violates angular-momentum balance. One must use angular momentum about an inertial point, or account for translation and changing material membership. A fixed-hinge reduction is defensible while pivot displacement is small compared with a, the attached mass distribution stays approximately constant, and contact-pulse detail lies outside the prediction of interest. Accurate release-to-contact timing cannot validate an acoustic waveform sampled thousands of times per second.

Bending, branches and anisotropy

For a slender beam at small incremental transverse deflection $w(s,t)$ around a specified posture, let $\mu(s)$ be line density, $B(s)$ bending rigidity, and $P(s) > 0$ compressive axial force. A representative equation is

$$\mu w_{tt} + \partial_s^2(Bw_{ss}) + \partial_s(Pw_s) = q_\perp.$$

It follows by varying kinetic energy and the quadratic potential $\int (Bw_{ss}^2 - Pw_s^2)ds/2$. The sign reveals how compression softens a bending mode. For a cantilever, displacement and slope vanish at an ideal fixed base; bending moment and effective transverse force vanish at the free tip. A compliant root instead couples base forces and moments to base motion. For uniform B, μ and $P = 0$, bending frequency scales as $L^{-2}\sqrt{B/\mu}$. The beam model can predict how the crown lags a suddenly moved trunk. The small-deflection equation in a fixed frame cannot describe a complete ninety-degree rotation. One can separate gross rotation from small residual strain, or use a geometrically exact rod. Short wavelengths comparable with branch diameter require shear deformation, rotary inertia or a continuum treatment.

The distinction is temporal as well as geometric. Write T_c for contact time and T_1 for the fundamental period. If $T_c \ll T_1$, the structure cannot adjust as though loading were static. The mass initially mobilized can be much smaller than total mass. A stress wave can propagate along the stem while an outer branch continues to fall. An effective contact mass may depend on frequency. Lundström and colleagues measured impact into standing Norway spruce using a guided mass, finding localized loading followed by distributed energy absorption. That geometry differs from a falling tree striking soil. The study supports load redistribution without supplying a transferable air-radiation coefficient [M3].

In a branching model, connect rods at graph vertices. A welded junction imposes a common displacement and rotation and balances the sums of forces and moments on incident edges, including concentrated junction inertia if assigned. A flexible crotch instead requires its own moment–rotation law. A modal reduction has the structure $M\ddot{q} + C\dot{q} + Kq + g_{\text{geom}}(q, \dot{q}) = f(t)$. Different modes can exchange energy through the geometric term even when C vanishes. A vanishing trunk oscillation can coexist with energetic branches. Transfer becomes a dissipative route when receiving modes lose energy through material damping or drag. Theckes, de Langre and Boutillon examined this effect in tree-inspired branched structures [M4]. A dashpot adjusted only to trunk data cannot identify how much energy reached an airborne wave. Motion records from the receiving branches could distinguish competing explanations.

The local material frame has longitudinal, radial and tangential axes. In the elastic range $\sigma_{ij} = C_{ijkl}(x)\epsilon_{kl}$. Orthotropic linear elasticity has nine independent stiffness constants subject to positive strain energy. Knots, reaction wood, decay, preexisting cracks, moisture gradients and grain orientation can control the rupture path. The USDA handbook describes these properties and their testing context [M5]. Values for clear dry specimens cannot simply be assigned to a wet, damaged standing tree. For gross rotation use the deformation gradient $F = \nabla_X x$ and reference momentum balance $\rho_{w0}\ddot{x} = \text{Div}_X P + \rho_{w0} g$. A stored-energy density depending on F, material position and internal damage variables gives the elastic contribution to the first Piola stress P. Its objectivity requires invariance under rigid spatial rotation of F, while the material directions remain tied to the reference body. Choosing constitutive functions and independently identifying all of their parameters remain separate problems.

Fracture, contact and aerodynamic loading

A crack releases potential energy per incremental area $G = -\partial\Pi/\partial A$ in a specified quasi-static loading problem. The elementary growth criterion compares G with the material resistance G_c. Dynamically advancing cracks also exchange energy with stress waves and fragment motion. A cohesive traction law $t(\delta)$ on separating faces gives work $\int t\,d\delta$ per area for a specified mode and history. Spruce specimens show bridging behind the crack tip; treating every new surface as a brittle cleavage plane would omit this contribution [M6]. Branch tearing or delamination can create distinct impulses before ground contact. The first consequence is a change in stress and acceleration. Coupling to air is determined by what happens at exposed surfaces.

For unilateral contact use a signed separation d and compressive force λ_n. A rigid model requires $d \geq 0$, $\lambda_n \geq 0$, $d\lambda_n = 0$. A compliant model resolves indentation. The impulse $J_n = \int F_n dt$ fixes change in normal momentum after other impulses are accounted for. It does not fix force spectrum. Pulses delivered in a tenth and a hundredth of a second can have the same impulse and very different high-frequency radiation. Even the spectrum of force on the *soil* fails to determine the force on the *air*.

Elastic smooth spherical contact gives the Hertz law $F_n = K\delta^{3/2}$ and reversible energy $2K\delta^{5/2}/5$, with $K = 4E^*\sqrt{R^*}/3$ [M7]. A log contacting the ground along much of its length violates the spherical assumption. Rough peat and snow can compact irreversibly. Isolated branch strikes and subsequent rocking deliver pulses at different positions and times. For a single isolated normal degree of freedom with restitution e, the kinetic loss is $(1-e^2)m_{\text{eff}}v_n^2/2$. It combines fragmentation, transfer to unresolved motion, heating and radiation. Measuring rebound accurately does not justify assigning this whole quantity to sound.

Aerodynamic loading depends on relative velocity. A quasi-steady transverse force element has the proposed form $dF_D = \rho_a C_D b|U_{\text{rel}}|U_{\text{rel}}\,ds/2$, where velocity is taken in the direction of airflow relative to the branch. The projected width b and coefficient C_D depend on geometry and flow. The moment is $d\mathbf{M} = \mathbf{r} \times d\mathbf{F}_D$. Foliage reconfiguration and detachment change the area. The rotational energy left in a wake differs from longitudinal energy transported acoustically. In a windy forest, wind can supply net work to the falling tree. Correcting a recorder only for the wind-dependent transfer path can leave an apparent efficiency biased because the loading itself changed.

The coupled description joins wood momentum balance, a solid or poromechanical soil model, and compressible fluid equations. At intact interfaces normal velocities match and normal tractions balance. An inviscid fluid loads the solid mainly in pressure, while a viscous no-slip model also constrains tangential motion. Fracture changes topology and exposes fresh boundaries. Soil surface waves transport energy as well as body waves. A saturated root zone can excite pore-pressure transients. Replacing this description with a pivot plus a waveform removes these mechanisms, each of which represents an uncertainty. Conversely, a finely discretized anisotropic fracture front with guessed material properties is a poor way to test a claim that depends only on whether *some* airborne radiation is possible.

Enclosing the channels once

Choose a control surface through air and soil and a time interval ending at T. Define released energy as the signed reduction in gravitational potential energy, plus signed nongravitational external work and the decrease of previously stored energy available for transfer. A guiding restraint or adverse wind can remove energy, in which case its external work is negative. In an explicitly background-subtracted experiment, with a consistent reference, the following balance expresses the proposed channels:

$$E_{\text{release}} = E_{\text{air,out}} + E_{\text{ground,out}} + E_{\text{fracture}} + E_{\text{thermal}} + E_{\text{deformation}} + E_{\text{residual}}.$$

The first terms integrate net flux through specified portions of the boundary. Fracture includes retained new surface or damage energy; dissipative cohesive work booked as heat is excluded. Deformation is recoverable stored strain relative to a specified reference and separately retained compaction energy if distinguished. The residual includes remaining kinetic motion, near-field elastic or acoustic storage inside the surface, eddies, and energy in escaping fragments or other advected material. Previously stored energy released and newly retained energy must be resolved consistently by region or mode; equivalently one can put all strain energy on one side as a net change. A residual can close the identity by definition. The measurement becomes informative only if independent data bound the residual.

If a pulse crossed the control surface and later heated distant air, its joules must not also appear as thermal loss *inside* the surface. Moving the surface outward to encompass the region of attenuation changes the entries. Long integrations introduce unrelated flows. A reproducible output specifies surface, band, time window and source attribution. Radiated energy near a source differs from energy surviving to a distant microphone's passband. Subtracting measured background *energy* from total energy in a linear model also introduces an interference cross term. The isolated event field has nonnegative quadratic energy, whereas a difference of noisy total energies can be negative. Matched controls address the observational distinction statistically.

For a one-tonne retained mass descending ten meters at the selected gravity, the available gravitational work is 98.1 kJ. This bounds a single channel only if no other source supplies work, no additional prestress is released, the other entries are nonnegative, and the measurement isolates event-generated energy. If 98.1 J crosses the specified air surface, the efficiency for this example is 10^{-3}. This conditional is a target for measurement, not a field observation. A smaller upper bound needs information on soil work, fracture or retained motion. A positive lower bound needs an imposed source constraint. The next chapter supplies one such constraint and shows why physical existence alone gives no universal lower limit on loudness.

3. From compressible motion to acoustic radiation

A pressure perturbation attributable to the fall

A barometer changes as weather moves across a forest. A microphone in a wake can register turbulent pressure. A leaf moves in response to a slowly changing load. None of these measurements alone establishes that the tree sent an acoustic disturbance across the woods. Specify a reference history without the collapse, with common incoming wind and sound as far as the experimental design permits. Treat the event field as the attributable change in pressure, density and velocity. In linear acoustics the difference solves a forced equation with the changed source and boundary conditions. For nonlinear fluids the difference of two solutions generally has coefficients dependent on both histories. Attribution then depends on a structural model of the counterfactual. Averaging over weather histories answers an ensemble question. It cannot supply the missing control waveform of a particular historical fall.

In acoustic motion the compressive pressure field and longitudinal velocity exchange energy. Entropy and vorticity disturbances have different constitutive relations and propagation speeds. In an ideal gas an isobaric entropy perturbation can change density without initially launching a traveling pressure wave. A transverse vortical disturbance can have velocity without first-order acoustic pressure. Even a uniform pressure offset does not by itself supply an outgoing pulse. Total pressure, density or velocity at one instant does not decide radiation. A field close to a vibrating object can also store and restore energy. Outgoing intensity, a positive radiation resistance, or projection on propagating modes is a more discriminating criterion when the intended meaning is energy carried away.

Derivation from conservation laws

Let ρ, u, p, e, T, τ denote fluid density, velocity, thermodynamic pressure, specific internal energy, temperature and viscous stress. In a local inertial frame, away from solid boundaries and with body acceleration b,

$$\partial_t \rho + \nabla \cdot (\rho u) = 0, \qquad \partial_t (\rho u) + \nabla \cdot (\rho u \otimes u) = -\nabla p + \nabla \cdot \tau + \rho b.$$

Writing $E = e + |u|^2/2$ and $q = -\kappa \nabla T$ for conductive heat flux, conservation of energy gives

$$\partial_t (\rho E) + \nabla \cdot [(\rho E + p)u - \tau u + q] = \rho b \cdot u.$$

Closure is required. In an isotropic Newtonian fluid the viscous stress separates into twice shear viscosity times the traceless strain-rate tensor and a bulk-viscous part proportional to the divergence. An equation of state supplies $p(\rho, s)$, where s is specific entropy. In a forest one can subtract hydrostatic equilibrium and resolve spatial scales on which background variables vary appreciably. The simplest local description assumes a constant

rest state, negligible body-force perturbation, small perturbation Mach number and heat exchange slow over one period. With $c^2 = (\partial p/\partial \rho)_s$, first-order conservation becomes

$$p' = c^2 \rho', \qquad \partial_t p' = -\rho_0 c^2 \nabla \cdot u', \qquad \rho_0 \partial_t u' = -\nabla p'.$$

Differentiating the pressure equation and substituting the velocity equation yields $c^{-2} p'_{tt} - \Delta p' = 0$ away from the source. A compact volume injection of total rate $Q(t)$ gives $\rho_0 \dot{Q}(t)\delta(x)$ on the right. A concentrated force $F(t)$ exerted *on the fluid* gives $-F(t) \cdot \nabla \delta(x)$. These idealizations require small source size relative to relevant wavelengths and distances. Replacing a twenty-meter tree by a single compact point throughout the entire human hearing band would violate the length-scale requirement. Individual subsources can instead be summed with their own retarded times and locations.

Multiplying pressure balance by $p'/(\rho_0 c^2)$ and momentum balance by u' gives

$$\partial_t e_a + \nabla \cdot I_a = 0, \qquad e_a = \frac{p'^2}{2\rho_0 c^2} + \frac{\rho_0 |u'|^2}{2}, \qquad I_a = p' u'.$$

Energy density has units J m^{-3}, intensity W m^{-2}. A locally plane outgoing wave has $u'_r \simeq p'/(\rho_0 c)$ and characteristic impedance $Z = \rho_0 c$. Integrating normal intensity over a surface and time gives transmitted energy. ISO 9614-1 describes related enclosing-surface techniques for sound power; its discrete-point method has specific applicability conditions, and a nonrepeatable outdoor transient requires a separate design [M8]. Pressure squared divided by Z can overestimate net flux in a standing field, where oppositely directed waves store positive energy despite zero average net power. An instrument measuring only pressure should report pressure exposure until a propagation approximation justifies inferring flux.

Linearization fails if nonlinear advection or amplitude-dependent phase speed accumulates sufficiently. An exact rearrangement in a force-free fluid with constant reference state gives Lighthill's identity

$$\partial_t^2 \rho' - c_0^2 \Delta \rho' = \partial_i \partial_j T_{ij}, \qquad T_{ij} = \rho u_i u_j + (p - p_0 - c_0^2 \rho')\delta_{ij} - \tau_{ij}.$$

Modeling turbulent stress without acoustic feedback is an additional approximation [M9]. A rigid boundary contributes surface loading, while a moving boundary introduces displacement effects as well [M10, M11]. An exposed tree can accelerate air during rotation, load the fluid through changing surface pressure, vibrate newly exposed fracture faces, expel air from closing gaps, or generate wake stresses. Rigid translation of a closed constant-volume body has $\int_{\partial B} u_B \cdot n \, dS = dV/dt = 0$. Using a monopole equal to the swept frontal volume would invent a leading source whose opposite contributions cancel. Dipole and distributed terms can remain.

For a weak, locally plane progressive sinusoid in lossless fluid, pressure amplitude p_* and angular frequency ω give a steepening distance of order $\rho_0 c^3/(\beta \omega p_*)$. Taking characteristic speed $c + \beta p'/(\rho_0 c)$ and asking where neighboring phases overtake gives this scale. In a perfect gas $\beta = (\gamma + 1)/2$. A sharp local pressure rise is insufficient evidence for a

propagating shock. Spreading and dissipation can reduce amplitudes before significant steepening develops. It is physically consistent for wood deformation to be strongly nonlinear and the later acoustic field to propagate linearly.

Compact multipoles and a conditional sharp bound

The outgoing free-space Green function of $c^{-2}\partial_t^2 - \Delta$ is $\delta(t - r/c)/(4\pi r)$. For a compact monopole it gives $p'_M = \rho_0 \dot{Q}(t - r/c)/(4\pi r)$. A point force yields

$$p'_D(rn, t) = \frac{n \cdot \dot{F}(t - r/c)}{4\pi c r} + O(r^{-2}).$$

Differentiating the spatial kernel also yields a term proportional to $n \cdot F/r^2$. Its relative role increases within order one reduced wavelength. For an extended source of diameter D, a distance-independent directivity pattern requires negligible phase curvature over the source as well as $r \gg D$. In a homogeneous medium this involves $kD^2/r \ll 1$ up to a geometry factor. A microphone can be simultaneously far from one cracking twig and near the crown as a whole. Different arrivals in its record can require different propagation approximations.

Using $\int n_i n_j \, d\Omega = (4\pi/3)\delta_{ij}$ gives the integrated free-space energies

$$E_M = \frac{\rho_0}{4\pi c} \int |\dot{Q}|^2 dt, \qquad E_D = \frac{1}{12\pi\rho_0 c^3} \int |\dot{F}|^2 dt.$$

A monopole radiates isotropically, whereas a dipole of fixed orientation has a nodal plane. A zero at one microphone is compatible with strictly positive integrated power. Other sources, reflections and scattering usually fill idealized nodes. With the temporal transform $\widehat{F}(\omega) = \int F(t) e^{i\omega t} dt$, the two-sided energy spectrum is proportional to $\omega^2 |\widehat{F}(\omega)|^2$ with Parseval factor $1/(2\pi)$. A one-sided spectrum doubles positive-frequency contributions for a real signal. A power spectral density formed over a finite record depends on window and duration. It does not equal radiated energy spectrum without normalization and path correction.

Proposition. In the compact, pure-dipole model let force F vanish outside $[0, T]$, be absolutely continuous on the interval, have zero endpoint values and a square-integrable derivative. If the impulse imparted to the fluid is $J = \int_0^T F(t) dt$, then

$$E_D \geq \frac{|J|^2}{\pi \rho_0 c^3 T^3}.$$

Proof. Integration by parts gives $J = -\int_0^T (t - T/2) \dot{F}(t) dt$. Vector Cauchy–Schwarz and $\int_0^T (t - T/2)^2 dt = T^3/12$ give the bound after substituting the dipole energy. Equality is attained for $F(t) = 6Jt(T - t)/T^3$ in the interval. The resulting quantity has units of joules. This is a sharp conditional application of an established inequality without a priority claim. Its impulse is aerodynamic impulse, which cannot be inferred merely from the momentum

deposited by a trunk into the soil. It treats the effective dipole as the only sound source; contributions or cancellations from other mechanisms require a different model. The finite-size approximation is justified only over frequencies carrying appreciable energy. Mathematical equality in the prescribed point-source model is not a claim of attainment by a real tree.

For a smooth-endpoint pulse $F(t) = J[1 - \cos(2\pi t/T)]/T$ on the interval, radiation equals $\pi|J|^2/(6\rho_0 c^3 T^3)$. Select illustrative values $|J| = 10$ N s, $\rho_0 = 1.2$ kg m^{-3}, and $c = 343$ m s^{-1}. Durations of 0.02, 0.05 and 0.20 s give 0.1352, 0.008650 and 0.0001352 J respectively. Relative to the 98.1 kJ example these correspond to 1.38×10^{-6}, 8.82×10^{-8} and 1.38×10^{-9}. These analytic scenarios show what holding impulse fixed entails. No measured impulse or duration associates them with particular species or biomes. A softer landing that lengthens actual aerodynamic loading at constant impulse reduces radiation in this model. If branches snap or a contact expels more air, the source itself has changed. Giving the three durations habitat names would not establish empirical forest performance.

The density limit illustrates another potential error. Prescribed Q gives monopole energy proportional to ρ_0/c. Prescribed force on the fluid gives dipole energy inversely proportional to ρ_0 at fixed c. It is physically inconsistent to hold that force and all mechanical conditions fixed to vacuum. For prescribed body motion, the linear fluid load itself decreases with density. Maintaining a fixed force eventually violates perturbation and energy assumptions. At sufficiently low density, molecular mean free paths cease to be small against the wavelength or body size; hydrodynamic sound then requires replacement by a kinetic description. Individual particles can still carry impulses without sustaining ordinary continuum sound.

Exact silence, volume forcing and an exposed boundary

Write $Lp = s$ for $L = c^{-2}\partial_t^2 - \Delta$ in a lossless, unbounded homogeneous fluid initially at rest. Assume s smooth and compact in space and time. The outgoing Helmholtz kernel and its expansion at large r give a far-field spectrum in direction n proportional to $\tilde{s}((\omega/c)n, \omega)$, with spatial transform convention $e^{-ik\cdot x}$ and temporal convention $e^{i\omega t}$. Only the dispersion surface $|k| = |\omega|/c$ is sampled. Apart from a positive normalization, total radiated energy is the integral of the squared magnitude of this restriction over direction and frequency. Nonzero restriction on a set of positive measure is therefore necessary and sufficient for positive finite radiated energy in this model. For a smooth compact source, a nonzero value at a single positive frequency and direction remains nonzero in a neighborhood. A strictly monochromatic excitation extending over infinite time should instead be described by average power.

This result yields a constructive counterexample. Choose any nonzero smooth compact spacetime bump ϕ, zero before onset, and take $s = L\phi$. Its unique retarded solution is $p = \phi$. The forcing is active and there is an interior field, yet the exterior field vanishes. In Fourier space the multiplier $|k|^2 - \omega^2/c^2$ vanishes on the dispersion surface. Adding this s to another forcing changes the source while preserving every exterior recording. Nonradiating source distributions and their inverse-problem implications are established prior art [M12]. This construction applies to arbitrary independently driven volumetric

forcing. It supplies neither a passive tree design nor evidence that an exposed falling tree spontaneously coordinates such a source.

Proposition for an exposed vibrating body. Suppose a bounded solid with smooth fixed reference boundary has connected exterior filled with a homogeneous lossless fluid at rest. At a positive frequency, impose a prescribed surface-normal velocity v_n in linearized impermeability. The exterior has no other source, no incident field and satisfies the Sommerfeld radiation condition. With $e^{-i\omega t}$ convention and the normal from solid to fluid, $\partial_n p = i\rho_0 \omega v_n$. A nonzero v_n implies positive time-averaged outgoing power.

Proof. The far-field form is $p(rn) = e^{ikr} p_\infty(n)/r + O(r^{-2})$, and the power is $(2\rho_0 c)^{-1} \int |p_\infty|^2 d\Omega$. If it is zero, continuity gives a vanishing far-field pattern. Rellich's lemma and unique continuation give zero pressure throughout the connected exterior [M13]. Its normal derivative also vanishes, contradicting nonzero v_n. Conversely zero prescribed velocity without incident or volume sources gives zero by outgoing exterior uniqueness. The transient counterpart applies on any positive-measure band where the boundary forcing is nonzero. This argument is a corollary of an established scattering result. It does not demand a net volume change: a vibrating surface with zero integral of normal velocity may have nonzero normal velocity locally and radiate.

The premises exclude distributed exterior forcing, sealed interior cavities, large moving boundaries, topology changes and a waveguide below cutoff. Purely tangential motion supplies no normal velocity in a slip model. Finite viscosity and later shape changes may alter actual coupling. This proposition establishes no universal lower energy. Multiplying a prescribed boundary velocity by any positive ϵ multiplies power by ϵ^2. Exact nonzero energy can therefore be smaller than any stipulated operational threshold.

An ordinary tree changes shape and moves exposed surface elements with substantial normal motion. Fracture and contact introduce further transients. These mechanisms support expecting radiation during several stages of the fall. A theorem about *every* realizable tree collapse in *every* atmospheric geometry would require specification of the admissible mechanical histories and control over any compensating sources and boundaries. We have no verified exactly silent counterexample for an ordinary passive free fall in open terrestrial air and no unrestricted necessity theorem for that class. An ideal shield or a vacuum changes the premises. A finite-band experiment in finitely many directions can bound radiation in the measured channels. It cannot certify exact zero over every mode.

Dissipation, impedance and the inverse source problem

For normal incidence between homogeneous semi-infinite fluids with real impedances Z_1, Z_2, pressure and normal velocity continuity give a pressure reflection coefficient $(Z_2 - Z_1)/(Z_2 + Z_1)$ and energy transmission fraction $4Z_1Z_2/(Z_1 + Z_2)^2$. In solids, oblique coupling can also excite shear waves. Layered porous soil admits absorption and frequency-dependent complex impedance. A rigid reflecting plane has unit pressure reflection and vanishing normal fluid velocity; a matched absorbing boundary suppresses the return but the incident energy still reached it. Boundary scattering can alter the *source* radiation impedance as well as the transmitted path. Multiplying free-field power

by propagation loss cannot automatically recover near-source mechanical feedback.

In a homogeneous weakly dissipative continuum gas the classical amplitude attenuation is

$$\alpha_{\mathrm{cl}} = \frac{\omega^2}{2\rho_0 c^3}\left[\frac{4}{3}\mu + \zeta + \kappa(1/c_v - 1/c_p)\right],$$

with shear viscosity μ, bulk viscosity ζ, thermal conductivity κ and specific heats per unit mass c_v, c_p. Each bracketed term has units of viscosity. The weak-loss result assumes locally equilibrated modes represented by these coefficients. Relaxation adds frequency dependence. Atmospheric absorption estimates require temperature, humidity, pressure and frequency within a stated empirical domain [M14]. A relaxation process already included in an effective bulk viscosity must not be added again through a second fitted term. At fixed direction, an outgoing wave in homogeneous still air has amplitude proportional to $r^{-1}e^{-\alpha r}$ and intensity proportional to $r^{-2}e^{-2\alpha r}$. Wind gradients and canopy scattering change routes, phases and arrival times. A weakened direct arrival can reflect redistribution to other directions even without substantial heat production.

An inverse problem starts with $Y_j(\omega) = H_j(\omega)S(\omega) + N_j(\omega)$ only when a common scalar source suffices. Multiple rupture sites require a source vector and a transfer matrix. One record cannot separate an arbitrary unknown source from an arbitrary path. For any smooth gain nonzero over the measured band with bounded inverse there, an adjusted source and inversely adjusted path reproduce the same observation. Calibrated test signals can estimate parts of H; synchronized receivers constrain delays; structural priors restrict admissible impulses. A transfer zero on a band leaves that band undetermined without additional assumptions, while tiny singular values make deconvolution unstable despite formal uniqueness. A record sufficient to establish that an event reached one microphone need not establish the total radiated energy, detailed crack history or identity of an individual unmarked tree. Conversely, a failure to reconstruct the crack history can coexist with compelling evidence that the event radiated.

4. The forest as a propagation experiment

What can be transferred between stands?

A measurement beside the root plate answers a different physical question from one made beyond a ridge. The first can include fluctuations in aerodynamic pressure, motion transmitted through a microphone mount, and pressure associated with displacing air. The second can be dominated by only a few bands and directions of the outgoing field. Even when both records arise from one collapse, dividing their spectra need not recover a property of the forest. A translating, branching and fracturing source can illuminate the receivers differently. Define propagation with a specified source, receiving observable, environmental state and clock.

Let $b(\mathbf{y}, \tau)$ denote an equivalent source density after the moving tree boundary has been represented on a fixed domain. For a known history m of the forest and a linear propagation model, the causal response is

$$p(\mathbf{x}, t) = \int_{-\infty}^{t} \int G_m(\mathbf{x}, t; \mathbf{y}, \tau) b(\mathbf{y}, \tau)\, d^3y\, d\tau.$$

Here G_m is the pressure response to an impulse in the specified source convention. A vector force density contracts with the appropriate derivative or vector kernel. A scalar monopole alone cannot encode the orientation of a breaking branch. Changing the operator normalization also changes the dimensions assigned to the impulse and G_m. Their product under integration has pressure units. If wind, leaves and temperature are effectively frozen during the source-to-receiver travel time and across the measurement window, G_m is a function of lag $t - \tau$. A Fourier transform then defines a transfer function. A fall in a rapidly changing gust may require different kernels for the early and late parts of the source. It is then easy to misinterpret a change in propagation gain as a change in the spectrum radiated by the tree.

For a resting fluid with spatially varying density ρ and adiabatic compressibility κ, neglecting gravity-wave effects and time evolution of the background, the frequency operator for pressure is $\nabla \cdot (\rho^{-1} \nabla p) + \omega^2 \kappa p$. Adopt time dependence $e^{-i\omega t}$, for which an outgoing homogeneous solution is proportional to e^{ikr}/r. In a passive attenuating fluid take $\operatorname{Im}(k) \geq 0$. For a locally reacting soil, the complex surface impedance Z_g relates pressure to the normal velocity directed into the soil. At incidence angle θ from the surface normal, continuity of pressure and normal velocity gives the plane-wave reflection coefficient

$$R_p = \frac{Z_g \cos\theta - \rho c}{Z_g \cos\theta + \rho c}.$$

The rigid limit gives $+1$, the pressure-release limit -1. Finite complex impedance can shift cancellation bands relative to either limit. At finite source range, multiplying a spherical mirror source by this plane-wave coefficient is approximate. Layered soils and snow can support behavior missed by a single image, particularly near grazing incidence or in a surface-wave contribution [F4, F5].

Distinguishable mechanisms of transmission loss

How much coherent forward pressure remains, how much wave energy crosses a whole surface, and how much energy is dissipated are distinct questions. Randomly spaced trunks can scatter directions and phases, reducing the coherent amplitude while increasing delayed energy at a station whose direct arrival is weakened. In a lossless model the coherent component gives up energy to other wave components. Dissipative losses instead convert organized motion into heat. A coefficient fitted to direct-arrival level includes both processes, often along with geometrical spreading and ground interaction; its extrapolation to another array geometry requires an independent test. Price, Attenborough and Heap compared measurements from three British woodlands with a model incorporating ground and vegetation contributions under neutral atmospheric conditions [F1]. Their spectral features characterize those sites and conditions.

A stem distribution should enter through acoustic size parameters ka, with a a representative radius. A stem can be acoustically small at an impact's dominant frequency and substantial at a branch-fracture frequency. Basal area, spacing and clustering matter separately. Corridors between trunks preserve paths at specific azimuths that an isotropic mean-density model erases. Leaves and needles introduce smaller length scales and can vibrate. The fraction of sky hidden in an upward canopy photograph cannot determine the path length through leaf area encountered by an oblique pulse. An acoustic inventory should archive terrain, source and receiver heights, trunk locations, understory and ground state in addition to a forest-type designation. Changes in the crown during the fall itself may alter both the source and the medium.

Padgham measured transmission in two Australian forests. The denser stand displayed stronger attenuation and a slower reverberative decay, a combination concealed by a single descriptor of sound loss. Source and receiver heights also mattered [F2]. Ellinger and Hödl measured environmental transfer and background sound in a Venezuelan lowland rainforest, separating the frequency and height dependence of transmitted sound from ambient temporal changes [F3]. A fixed signal can become much harder to recognize at a particular hour even if the transfer function has barely changed. Alternatively, a changing wind profile can redirect an arrival while its background level remains stable.

Atmospheric absorption depends on frequency, temperature, pressure and humidity along the path. With an amplitude coefficient α in nepers per metre, the straight-ray factor is $\exp[-\int \alpha(f,s)ds]$. A tabulated positive loss a in dB/m gives $\alpha = a\ln(10)/20$ for pressure; squaring the amplitude then gives energy loss. Reapplying the same decibel factor to an already attenuated energy doubles the modeled loss in decibels. ISO 9613-1 provides an atmospheric-absorption calculation over a defined range of conditions [F6]. For weak wind, an effective-speed travel-time estimate is $\int ds/(c + \mathbf{u}\cdot\mathbf{n})$ along a ray with direction $\mathbf{n}$. Vertical gradients bend rays. Integrating along an assumed straight line cannot reproduce a shadow boundary created by such bending.

Rain supplies a background of impacts on vegetation, changes surface moisture, and can produce capsule or windscreen artifacts. It can also covary with the probability of collapse. During five years of approximately monthly drone observations in Panama, Araujo and colleagues found a relationship between extreme rainfall frequency and canopy dis-

turbance [F7]. Time resolution limits the attribution of any individual failure to a gust or shower. The result nevertheless identifies a sampling problem. A detector calibrated during quiet weather and applied to storm-driven events can encounter changed distributions of both event type and noise. Treating rainfall solely as a coefficient of propagation misses these selection effects.

A solvable acoustic map and its conservation audit

An exact control reveals which spatial effects can arise without vegetation. Place a stationary monopole at height h over an infinite rigid plane. For the normalized operator $c^{-2}\partial_t^2 - \nabla^2$ the impulse response is

$$G_N(t) = \frac{\delta(t - r_d/c)}{4\pi r_d} + \frac{\delta(t - r_i/c)}{4\pi r_i},$$

where r_d and r_i are the distances to the real and mirror sources. The singularity in the physical domain has the free-space normalization, reflection symmetry enforces zero normal velocity, and the outgoing condition supplies the causal solution. For horizontal range x and height z the two distances obey $r_{d,i}^2 = x^2 + (z \mp h)^2$. The earliest possible wavefront arrives at r_d/c. An instrument may mark a later arrival or fail to mark any arrival depending on its passband, noise and decision criterion.

For a separate numerical control prescribe $h = 3$ m, $c = 343$ m/s, $\rho = 1.20$ kg/m³ and two source frequencies, 256 and 1,024 Hz. Normalize each emitted peak pressure-distance coefficient to $A = 1$ Pa m. These are specified design inputs. No tree was measured, and this fixed-strength source excludes boundary-induced mechanical changes in the source. After both wavefronts arrive and stationary tones persist, the combined RMS pressure is $\sqrt{(|p_{256}|^2 + |p_{1024}|^2)/2}$ over common periods. Linear momentum gives $\mathbf{v}_j = \mathbf{n}_j p_j (1 + i/(kr_j))/(\rho c)$ for each outgoing spherical contribution. Sum coherent fields within each frequency before forming its time-averaged active intensity $\frac{1}{2}\mathrm{Re}(p\mathbf{v}^*)$. Then sum the two vector intensities. Scalar pressure squared divided by impedance everywhere would misrepresent the energy flow near interference minima.

On a grid of 641 horizontal positions and 241 heights the direct wavefront arrives from 11.66 to 234.71 ms after emission. For a specified, spatially uniform two-band noise level of 0.05 Pa RMS, combined SNR ranges from −17.69 to +18.04 dB. This is a ratio of signal and noise energies in the admitted bands. A detection probability also requires distributions and a decision rule. The spectral distortion map shows the high-to-low amplitude ratio in decibels relative to the equal prescribed source strengths. Destructive interference greatly reduces one band at some locations. The displayed range is clipped for legibility and the complete numeric arrays are included. The reflection-gain map compares received 1,024 Hz pressure with the direct free-space pressure. Enhanced and reduced levels coexist even though the boundary absorbs no energy.

An independent integral identity tests the computation. Integrate outward active power over a hemisphere of radius $R > h$ centered on the plane directly below the source. The free-space monopole power is $W_0 = 4\pi A^2/(2\rho c)$. In the far zone the rigid-plane angular

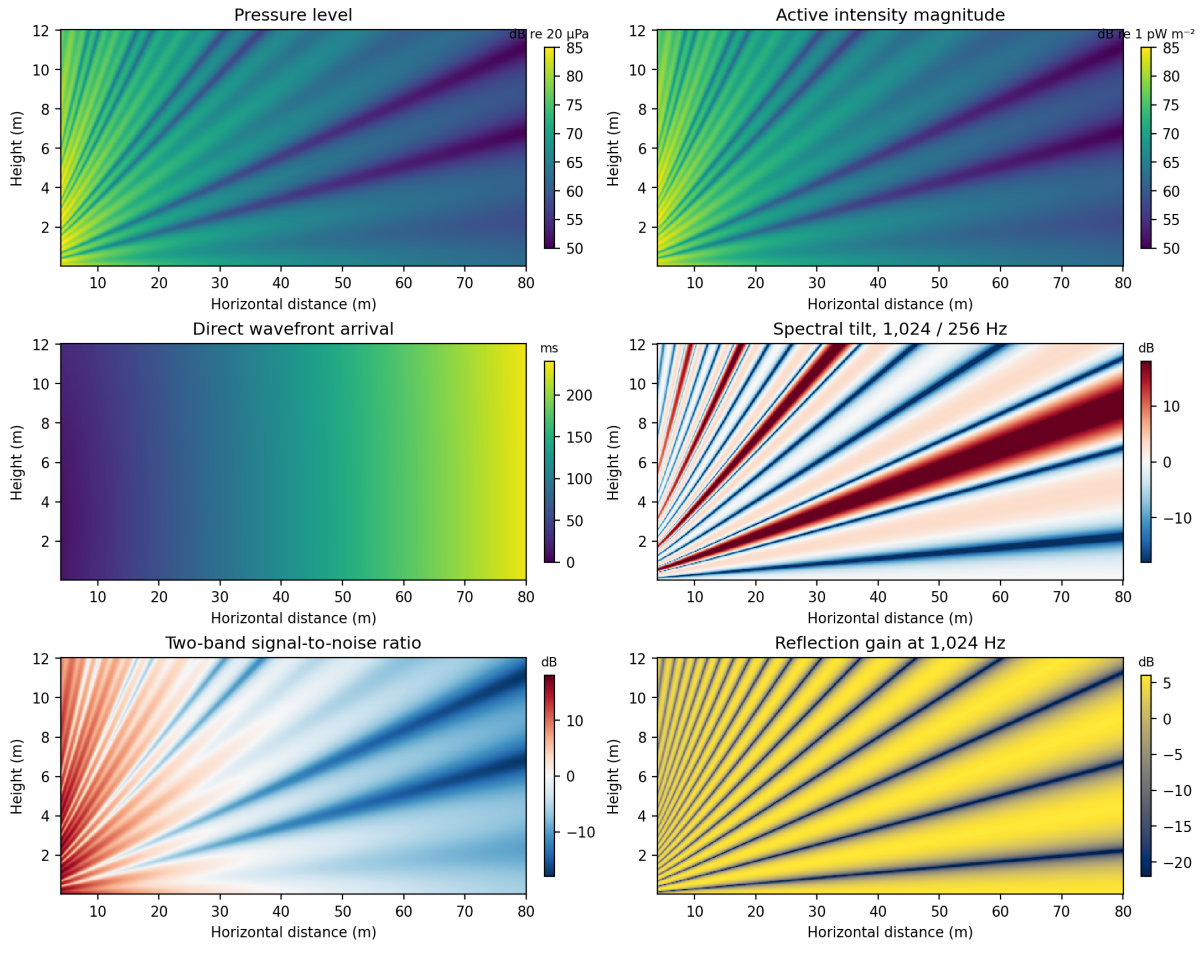

Figure 2: Rigid-half-space control. The panels separate pressure, active intensity, first wavefront arrival, spectral distortion, assumed two-band SNR and the effect of reflection. These are analytic model outputs.

pressure amplitude is proportional to $2\cos(kh\cos\theta)/R$. Integration of its squared modulus over the hemisphere gives $W/W_0 = 1 + \sin(2kh)/(2kh)$. Zero flux at the boundary and energy conservation make the result independent of R. Numerical quadrature at finite radii of 12 and 40 m retained exact directions, phases and reactive velocity contributions. At 2,049 angular nodes all relative discrepancies were below 10^{-8}. The modeled normal boundary velocity vanished on the sampled plane. This audits phase conventions, spherical corrections and the vector-intensity implementation. It establishes no forest-specific parameter.

Biomes, perfect absorption and accessibility

Old growth refers to stand structure or disturbance history; tropical and boreal classify climatic zones. One site can have both designations, so the categories are not independent treatments. The following are conditional predictions and proposed discriminating observations rather than a cross-biome ranking.

Setting	Quantities to measure	Prediction or test
Old-growth woods	Trunk map, gaps, understory, vertical crown structure, debris and terrain	Transects of equal length can differ in early-to-late energy ratio. Compare an open gap axis with a closed transect at matched heights.
Tropical rainforest	Rain, vertical leaf-area profile, background spectrum, time of day, soil moisture	Changes in ambient spectrum can shift detectable range even at nearly constant calibrated transfer [F3].
Boreal forest	Snow depth and layering, frozen or thawed soil, stem spacing, wind	A vertical array can separate a near-ground surface contribution from a change in direct transmission. Surface waves over snow have been measured [F5].
Sparse woodland	Exposed soil, trunk placements, slope and sensor heights	A direct-plus-ground model is a candidate for open lines of sight; residual errors concentrated behind trunks suggest a missing scattering path.
Perfectly absorbing forest boundary	Precise absorber location, frequencies and incident directions	A matched boundary removes its reflected path. The interior direct path still exists. Perfect absorption across all angles and bands is an ideal limit.

Van Renterghem and colleagues measured forest-floor impedance in six broadleaved stands with repeated seasonal observations. Ground state and moisture altered the observed behavior [F4]. Albert identified an acoustic surface-wave component over snow

using pulse shape and height dependence [F5]. One study motivates local impedance measurement; the other demonstrates how a late low-frequency arrival can arise without diffuse trunk scattering. Neither supplies a universal correction for boreal woods. A single receiver height could conceal the difference.

A ray shadow behind terrain or under upward refraction can contain substantial diffracted or scattered sound. At finite wavelength low-frequency energy can skirt an obstacle that attenuates a higher band strongly. An exact nodal surface at one frequency in a symmetric field is a different limiting case. A broadband transient can remain distinguishable there if another frequency retains evidence. Conversely, background noise or receiver directionality can hide an energetic wave. A claim of local inaccessibility should specify the band, time available for integration, receiver geometry and tolerated errors. The woods influence the conditions of observation and can cushion or interrupt the fall. A difference between open and wooded recordings is therefore insufficient to attribute the difference entirely to propagation.

To identify a field transfer, repeat monitored, band-limited sweeps from several source positions and heights. Estimate a receiver/reference cross-spectrum divided by the reference autospectrum and flag poorly coherent frequencies. Retain variability across repetitions. Complex averaging can cancel phase-variable but energetic late components. Compare direct propagation, an impedance boundary, and measured meteorology and terrain on held-out transects. Introduce canopy scattering when it improves specified error measures such as first-arrival time, band energy and late-to-early ratio. A one-way parabolic propagation model is poorly suited to a receiver dominated by backscatter. A full-wave calculation is only as accurate as the terrain, material properties, resolved wavelengths, boundary conditions and numerical convergence it can support. Apparent precision of a finely sampled map cannot compensate for an uncertain physical boundary.

Finally, consider $Y_i(f) = H_i(f)S(f)$. Replacing the source spectrum by $a(f)S(f)$ and every path kernel by $H_i(f)/a(f)$ leaves every observation unchanged for any nonvanishing admissible a. A calibrated reference, independently constrained source, or additional physics is necessary to assign absolute loss and efficiency. Ratios of receivers remove a common source only if the same radiation component illuminates them; a distributed oriented source can defeat that assumption. This ambiguity is physical and statistical. Reconstructing a treefall's field from a few stations requires an explicit test of the information supplied by the receivers versus information introduced by the prior.

5. Receivers, nervous systems, and the production of a sound

Which changes in the receiver matter to the source?

Consider a tree, a patch of ground, and a recorder whose switch is operated remotely. Suppose its case, windscreen, and diaphragm have effectively identical mechanical properties in the two switch positions. Turning off digital storage changes whether anyone will obtain a record. It need not appreciably change the tree's loading of the surrounding air. Replacing that recorder with a large rigid wall could change both the pressure at a particular point and the radiation impedance presented to the tree. Observer independence concerns the first kind of intervention. Physics makes no general promise that exchanging arbitrary physical bodies leaves the field invariant. The issue is whether the event requires an observer *in the role of observing*. A wall can exert its influence while its owner is attending to something else.

The Acoustical Society of America lists two technical senses of sound. One concerns propagated mechanical oscillation in a medium, including the superposition of propagated oscillations. The other concerns the auditory sensation such oscillation evokes. Its annotation explicitly gives examples of physical sounds that fail to elicit sensation and sensations that occur without such physical sound [O1]. This is a choice of referents available within a single standards vocabulary. It changes the truth conditions of the tree's *making* a sound. Under the first reading the relevant causal product lies in the coupled mechanical system. Under the second it lies in an organism and is caused by the mechanical system. Under both readings the tree has to be causally responsible for the specified product. A ringing sensation that happens to coincide with impact does not suffice.

Useful roles can be defined as predicates with different input and output types. A *present* body occupies a location during some interval. A *coupled* body changes state in response to the relevant component of the field. A *transducer* maps that change to a new variable, for example voltage or membrane potential. A *detector* supplies a decision variable for event and control conditions. A particular threshold crossing can still be a false alarm. A *recorder* retains a recoverable state beyond a declared interval. An *interpreter* attributes a retained or incoming signal to a process. An *experiencer* has a conscious auditory episode. An *investigator* uses evidence, assumptions and alternative explanations to infer a past event. These roles need no single common ordering. An investigator may reach a reliable conclusion from splinter patterns without using a microphone. A person may enjoy a brief sound, make no source judgment, and leave no accessible report. A recorder can store an uninterpretable waveform.

Entity	Accessible variable	Evidence needed for the stronger claim
Human	Binaural air-conducted input or bone conduction	Separate transduction, discrimination, identification and experienced quality

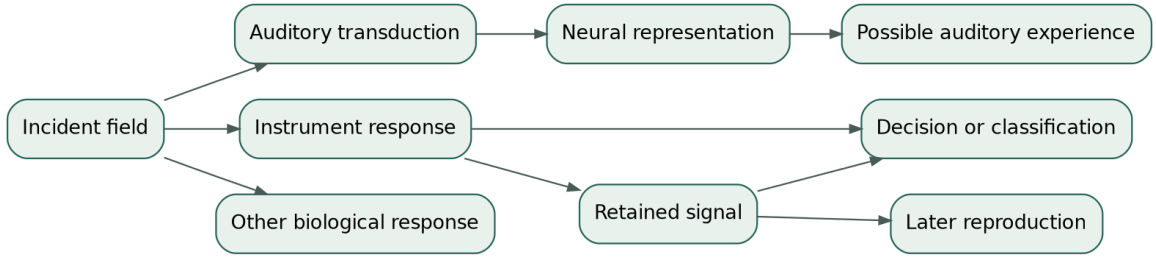

Figure 3: Receiver pathways. Transduction, decision, retained information and conscious experience have different conditions.

Entity	Accessible variable	Evidence needed for the stronger claim
Nonhuman mammal	Species- and individual-dependent auditory response	Calibrated behavioral or neural evidence for this waveform and state
Bird	Avian auditory transduction and orientation	Show usable cues under the relevant geometry
Insect	Species-specific pressure, particle-motion or substrate sensitivity	Establish the sense organ, stimulus and path
Plant	Tissue motion or subsequent physiology	Demonstrate selective causal response; auditory awareness does not follow
Microphone	Pressure- or pressure-gradient-dependent voltage	Validate transfer, noise and timing; storage requires another subsystem
Accelerometer	Acceleration along mounting axes	Separate substrate motion from case vibration and airborne pickup
Seismometer	Instrument-filtered ground motion	Establish ground coupling, orientation and competing sources
Distributed optical fiber	Gauge-averaged axial strain-related signal	Characterize installation, geometry and gauge response [O12]
Passive recording system	Sampled, timed representation	Establish completeness, clipping, provenance and survival
Autonomous robot	Sensor input, classified label or action	Independently validate decisions; classification does not demonstrate awareness
Ideal detector	Optimal test given a stipulated observation	Specify bandwidth, nuisance variables and noise law

A receiver hierarchy with branches

Source-attributable interaction is necessary for a genuine direct registration. A transient transducer output suffices for interaction without retention. A useful trigger requires discriminability as well as coupling. An archival measurement requires retention and an appropriate representation. An audit adds provenance and a way to check competing sources. On the biological branch a sensory response may contribute to discrimination, orienting or experience. Experience need not issue in a voluntary report. On the historical branch an investigator can arrive at a warranted attribution through testimony, imagery or ground traces. A memory card storing yesterday's wind noise supplies no evidence for today's tree, regardless of its capacity.

For a concrete derivation let x be an input history, s its tree-attributable component under an additive physical model, and L a linear receiver including orientation, mounting and bandwidth. Ignoring perturbation of the source by this small receiver, event and control output histories differ by Ls. If s lies in the null space of L, the two noiseless histories coincide even though $s \neq 0$. With the same independent additive noise law the output distributions also coincide, so every decision rule has the same probability of a positive decision in either condition. To prove the last assertion, integrate the rule, or its randomization probability, with respect to the common probability measure. Orthogonality to a single microphone response does not establish orthogonality to every admissible observation. A many-channel archive need not recover all source degrees of freedom. An array of identical co-located sensors can improve precision for some components when their noises differ while retaining exactly the same null space. This is linear algebra and statistical decision theory applied to a defined receiver. A nonlinear active receiver can have a different input equivalence relation.

An unattended microphone is a physical receiver. A powered unit connected to storage may also be an archive. In ordinary English "somebody" ranges over persons, so leaving this equipment behind is consistent with a site empty of people. A study may define an observer as any functioning evidence channel and the same site then contains one. Both statements agree on the material facts. The wider usage makes an unattended-recording test of *no evidence channel whatsoever* self-defeating by specification. It leaves an unattended test of *no person present at the time* entirely coherent. The clock and antenna are possible sources of contamination, which calibration and controls can address.

When subsequently played, the recorder drives a second radiator. The listener can hear evidence of the earlier tree through that causal chain. Production by the original tree, storage in a device, and playback by the loudspeaker have distinct locations and dates. If the file is never played there can still be a true archival statement that a waveform was recorded. If the file is later destroyed there can still have been such a registration. An audit may then fail. An automated classifier can produce evidence of recognition assessed against identified events. Its confidence score alone cannot establish the source of a single recording or an auditory experience.

From the pressure field to the auditory nerve

For air conduction in a human, the pinna, head and external canal filter the spatially varying input before it reaches the tympanic membrane. A pressure difference produces distributed membrane motion. The ossicles couple that motion to the oval window. Stapes motion drives cochlear fluid and produces a pressure difference across the cochlear partition. The round window helps accommodate fluid displacement. A traveling mechanical response peaks at different positions for different stimulus frequencies, with higher characteristic frequencies near the base and lower ones toward the apex. A sharp fracture and a slow impact can therefore recruit partly different regions even if a laboratory instrument reports identical integrated sound exposure. The relevant anatomy and frequency-to-place organization are established. This inference makes no assignment of frequency to a particular real tree [O2, O3].

External direction and timing survive this processing only selectively. One simplified representation at fixed head orientation is $p_e(t) = (h_e * p_{\text{inc}})(t)$ for ear e, where h_e includes the direction-dependent transfer to the eardrum and p_{inc} describes a single incoming direction. Forest multipath requires an angular superposition. A binaural listener thus receives two filtered sums over arrivals. Inferring where the collapse began is an inverse problem even before sensory transduction. Different source and reflection configurations can yield the same pressure pair at a stationary head over a limited band. Rotating the head can reduce that ambiguity by changing the measurement. Better localization cannot create radiation at the earlier impact.

Within the organ of Corti relative motion deflects hair bundles. Mechanically gated channels modulate receptor current. In mammalian inner hair cells the graded change in voltage controls calcium-dependent release of transmitter at ribbon synapses onto afferent neurons. Spike trains in auditory nerve fibers carry distributed information about the stimulus. Active outer hair-cell mechanics contribute gain, tuning and level-dependent behavior. Hudspeth reviews the evidence for this active process [O4]. Molecular and physiological experiments identify prestin as an outer hair-cell motor protein [O5], while the synaptic transfer step has its own evidence base [O6]. These stages constrain a passive frequency analyzer as a model. It may predict differences in band energy around a fixed operating point. It cannot establish equal perceived loudness merely by integrating two pressure spectra or assume a fixed cochlear gain across all input levels.

The auditory nerve is a useful conceptual boundary. Its response can be represented by a conditional law $P(N \mid p_e, z)$ on spike trains N, where z includes the organism's condition and other relevant inputs. An experiment might estimate how well two classes of sounds can be discriminated from N. That result is relative to the recorded population, stimulus distribution and decoder. It says neither that the organism uses precisely that decoder nor that its percept has the same resolution. A decoder trained to discriminate clean recordings of fracture from clean wind could exploit the onset of a timer if the apparatus introduces that cue. Independent exemplars and control timing are necessary if the claim concerns sensitivity to treefall structure. This problem persists even for accurate recordings and high classification accuracy.

From nerve activity to experience

Afferents reach the cochlear nuclei. Multiple ascending pathways carry timing, level and spectral information through brainstem and midbrain circuits, with binaural computations in circuits including the superior olivary complex. The inferior colliculus, medial geniculate body of the thalamus and auditory cortex figure in the major ascending system. Connections include parallel and bilateral paths as well as descending influences [O3]. A named relay gives neither a sufficient signature of awareness nor an instant at which the tree's sound is thereby made. An experiment can interrogate stimulus coding at one part of a circuit without resolving the state of the entire listener.

Hayat and colleagues recorded intracranial responses in human epilepsy patients during wakefulness and sleep. Auditory stimuli produced substantial responses in temporal regions during sleep, while especially the alpha–beta power changes differed between waking and sleeping states [O7]. This opposes the inference that all auditory transmission stops as soon as ordinary behavioral responsiveness declines. It does not measure consciousness on every trial. Sleep can include experiences, arousal can occur, and electrode coverage and participant population limit inference. Raveh and Lavie report reduced auditory detection sensitivity under high visual load in human experiments [O8]. A stimulus, location and nominally functioning ears can be held constant while task-dependent detection changes. Neither paper licenses the conclusion that any particular unattended animal had a specific experience.

Consider four tasks. In a two-interval trial a listener chooses which interval contained a transient. In a source-identification task the listener chooses wind, tree, animal or unknown. A participant may describe how an episode sounded. Finally the participant may report confidence in their earlier judgment. Performance on one task need not predict performance on another. Balanced forced choice allows estimation of a psychometric function against an explicit chance level. Verbal report introduces memory, language and reporting policy. A person who correctly identifies the interval without being able to identify the source supplies evidence of discrimination. The underlying physical event can still have a well-defined cause.

The inverse dissociation is equally important. Subjective tinnitus can involve an experienced sound without a matching external acoustic source [O9]. Auditory imagery can have recognizable timing and musical content during an actual gap in stimulation. Kraemer and colleagues examined such gaps using functional imaging [O10]. Imagining a falling tree may reproduce aspects of remembered timbre in a physically quiet room. That is a counterexample to an inference from *an auditory experience occurred* to *a tree produced an external wave*. For the narrower ASA sensory sense the sensation must be evoked by the physical oscillation [O1], so unrelated tinnitus cannot satisfy the causal verb *make*. Other internally audible phenomena can have mechanical origins inside the body. The place of origin, the existence of a physical signal, and dependence of an auditory quality on a listener are independent questions.

Nonhuman reception and the environment

Biological receivers cannot be pooled by counting heads or by drawing one circle around the tree. A mammal's ear, a bird's ear and an insect's antenna differ in what couples efficiently into them. Menda and colleagues combined behavioral and physiological methods to study airborne hearing in the mosquito *Aedes aegypti* [O11]. A sensitive biological receiver may be identified with species-specific stimuli and response measures. A measurement made only with a pressure microphone at another position will not in general specify the local vector particle motion at an antenna, especially close to a source. An insect responding through substrate vibration supplies evidence along a different physical path. Calling this "detection of the tree" leaves that path unspecified.

Appel and Cocroft used leaf vibrations associated with herbivore chewing to test plant responses and reported changes in subsequent defense [O13]. This evidence concerns a particular plant, stimuli and measured outcomes. It does not establish airborne treefall perception, an auditory nerve or plant awareness. Instrumented surface motion, a biological response and conscious interpretation are different experimentally accessible endpoints. To test them in a treefall study would require different controls. Mask airborne coupling while preserving substrate vibration, and reverse the manipulation while measuring residual cross-coupling. For an orienting animal add controls for visible movement, air currents and ground motion. For a chemical assay randomize handling and blind sample labels.

A claim that an animal heard without attending depends on the reading of "heard." Validated auditory-mediated discrimination can satisfy a biological detection criterion. A criterion of conscious experience needs evidence appropriate to the species and task. Absence of an attention task decides little by itself. When the premise excludes only people there is no contradiction in allowing nonhuman perception. When it excludes every possible local auditory subject, a locally evoked percept is absent by construction. Neither restriction fixes airborne radiation. A deaf person can be present, feel vibration, make a visual record and, depending on the person, signal and device, have residual or assisted hearing. Blanket inference from the identity label to a particular trial outcome has no basis.

The observer/environment boundary need not be arbitrary in every respect. Given an environmental partition and target variable, one can test whether its state carries a reproducible signature. Given an instrument one can measure whether its response changes when mounted and whether a file persists. What requires a stipulation is the choice of partition, purpose, allowable error and retention time that promote a coupled subsystem to a detector or archive. Even an ear can re-radiate energy. Kemp measured evoked acoustic emissions in the human auditory system [O14]. Treating hearers as mechanically absent is an approximation with a testable scale of error. Treating awareness as essential to the source term would require an entirely different premise.

6. What can an unheard pressure field specify?

The information question needs an alternative

Consider a clearing in which the trunk either fell this morning or had been resting on the ground for years. A photograph taken at noon might establish that a trunk is down with high confidence and tell us little about *when* it fell. A time-stamped sequence might settle the date yet tell us almost nothing about the pressure at a particular point behind a hill. Conversely, a record of pressure may identify an impulsive event yet leave its source ambiguous. These examples concern different unknowns. To ask how much information a sound contains, name the unknown, the recorded or available physical variables, their resolution, and the ensemble from which the alternatives are drawn. None of these choices is needed for the tree to deliver mechanical work to the air.

Let X specify a hypothesis or source parameter, F a finite set of coordinates of the exterior acoustic field, Y the variables accessible to a specified instrument, and Z the environmental context known in advance. Coordinates can be pressure samples averaged over finite volumes and times, coefficients in a band-limited mode basis, or pressure and particle velocity together. Assign a joint probability law conditional on Z. This law can express the variability of similar events, uncertainty in the parameters of one event, or a deliberately randomized laboratory design. Those interpretations lead to different numerical answers. With base-two logarithms, conditional mutual information is

$$I(X;F \mid Z) = \mathbb{E} \log_2 \frac{dP_{X,F|Z}}{d(P_{X|Z} \otimes P_{F|Z})}(X,F).$$

The expression uses a density ratio with respect to the indicated product law. For discrete variables it reduces to a sum over joint probabilities. If the joint law lacks the required absolute continuity, the divergence can be infinite. Specifying ideal real coordinates at infinite precision can therefore give formally infinite mutual information even for a noiseless scalar identity channel. A physical count in bits needs finite bandwidth, time, spatial access and uncertainty. The entropy $H(X) = -\sum_x P(x) \log_2 P(x)$ concerns a discrete source distribution. An outcome's surprisal $-\log_2 P(x)$ concerns one outcome under that distribution. Differential entropy for continuous coordinates changes under changes of units. These quantities answer different questions from the work delivered, measured in joules. [I1, I2]

For a fixed known event label $X = x_0$, $H(X) = 0$ whatever the field energy. Conversely, two weak disturbances whose measured projections have opposite signs can carry information about that sign even if nobody inspects the medium. Define a receiver by its possible coupling and uncertainty. Two conditional laws that differ on a measurable set A imply that membership in A can change the odds. Given positive prior mass for both alternatives, this establishes strictly positive mutual information between the label and the field coordinates. No measurement must actually be performed for the conditional laws to differ. The statement assumes a model of interventions or a population of alternatives. If weather drives both branch failure and distant wind noise, then the wind noise can

predict failure without having been produced by it. For the question about what the tree *makes*, distinguish causal transmission by the collapse from incidental statistical association. Holding background forcing fixed across a pair of forward simulations addresses that distinction within the model. Conditioning on an observed weather summary may leave unmeasured common causes.

A noisy experiment has an exact decision boundary

For a finite data window, suppose $Y = s_i + N$ under hypothesis $i = 0, 1$. Here s_i are known source-to-sensor waveforms and N is independent Gaussian noise with common symmetric positive definite covariance Σ. It may be colored and spatially correlated. With equal prior odds define the dimensionless separation d by

$$d^2 = (s_1 - s_0)^\mathsf{T} \Sigma^{-1} (s_1 - s_0).$$

Subtracting the two Gaussian log densities cancels quadratic terms in Y. The natural-log likelihood ratio is $(s_1 - s_0)^\mathsf{T} \Sigma^{-1} [Y - (s_1 + s_0)/2]$. Its variance is d^2 and its mean under the two hypotheses is respectively $-d^2/2$ and $d^2/2$. Thresholding at zero minimizes probability of error, which equals $\Phi(-d/2)$ for each class. For $d > 0$, a threshold controlling the false-positive probability at α gives power $\Phi(d - \Phi^{-1}(1-\alpha))$. Thus target power $1 - \beta$ requires $d \geq \Phi^{-1}(1-\alpha) + \Phi^{-1}(1-\beta)$. This result concerns one known pair and window. It cannot be applied to a search across thousands of unknown onset times at fixed family-wise false-alarm probability without adjusting the decision rule. Nor can it resolve an event whose signal and null models both omit a common confounder such as a rock impact. The result is a specialization of likelihood-ratio testing, with no novelty claim. [I2]

Distinguish receiver separation from pressure at a point. Correlated low-frequency wind noise and independent higher-frequency sensor noise can produce the same integrated noise variance while giving different d for a short fracture transient. Duplicating the data file cannot double d^2. Two independent observations of the same known waveform do double it. If two nominally identical channels have an equal signal amplitude a, equal noise variance σ^2 and correlation ρ with $-1 < \rho < 1$, direct inversion gives $d^2 = 2a^2/[\sigma^2(1+\rho)]$ against zero. The result approaches the single-channel value as ρ approaches one. Atmospheric noise shared across a clearing can limit the advantage of adding receivers. As ρ approaches minus one, the common signal can approach a noiseless sum; that extrapolation is specific to the assumed covariance.

The elementary case gives an instructive contrast in numerical scales. Let $d = 1$. Equal-prior optimal decision error is approximately 0.309, and power at one-sided false-positive probability 0.01 is approximately 0.092. These are standard-normal evaluations, without any tree data. Each conditional law is distinct, and many actual trials under the event would fail the test. The same tree radiates the same waveform whether an analyst sets the false-positive budget at one percent or ten percent. Stronger detection is possible if the observer knows the template and arrival time. A template learned from data that are then reused for testing can overstate performance. A falsifiable specification therefore includes independent data, the time-search rule, thresholds, and how nuisance variability enters both hypotheses.

From field energy to channel bounds

Represent the sampled field as $Y = GX + N$, where now X denotes random source-mode amplitudes with covariance K and G includes coupling, propagation and sensor response. Suppose N is independent zero-mean Gaussian noise with covariance $\Sigma \succ 0$. Gaussian distributions maximize differential entropy at fixed covariance. Since $h(Y \mid X) = h(N)$, substitution of output covariance gives [I1, I2]

$$I(X;Y) \le \tfrac{1}{2} \log_2 \det\bigl(I + \Sigma^{-1/2} G K G^{\mathsf{T}} \Sigma^{-1/2}\bigr)\,.$$

Equality holds for Gaussian X. The determinant factorizes into terms $1 + \lambda_j$ for eigenvalues of the whitened signal covariance. Each independent real Gaussian mode contributes $\frac{1}{2}\log_2(1+\lambda_j)$ bits. A fixed tree, a sparse family of fracture events and a Gaussian random source with the same covariance need not attain the same information. Capacity additionally takes a supremum over admissible input laws subject to a stated cost. For a real band-limited additive white Gaussian noise channel of bandwidth B, average received signal power P and in-band noise power N_B, the ideal capacity is $B\log_2(1 + P/N_B)$ bits per second under the conventional two-real-degrees-per-hertz-second count. A finite transient has no universally defined transmitted message or codebook. Its recoverable information about a binary event cannot exceed one bit, even in a channel with immense coding capacity.

Exact localization and exact waveform reconstruction pose distinct inverse problems. If K is positive definite and both source and noise are Gaussian, completing the square in the posterior density gives covariance $(K^{-1} + G^{\mathsf{T}}\Sigma^{-1}G)^{-1}$. Its trace in chosen source units is the minimum expected squared reconstruction error for a posterior-mean estimate. In whitened source coordinates $U = K^{-1/2}(X - \mathbb{E}X)$, a direction in the null space of $\Sigma^{-1/2}GK^{1/2}$ retains its full unit prior variance. Prior correlations can still reduce uncertainty about a *physical* coordinate indirectly related to a measured one. A narrow marginal posterior in such a coordinate can owe much to the prior. Stating that all posterior shrinkage represents independent waveform measurement would obscure this distinction. [I3]

For an independent scalar Gaussian source of variance v with squared-error distortion D, the rate-distortion function is $R(D) = \max[0, \frac{1}{2}\log_2(v/D)]$ for $D > 0$. The converse follows because $I(X;\widehat{X}) = h(X) - h(X \mid \widehat{X}) \ge h(X) - h(X - \widehat{X})$ and the error entropy is at most that of a Gaussian with the given mean-square error. For $0 < D < v$, equality is attained by constructing $X = \widehat{X} + E$ with independent centered Gaussians of variances $v - D$ and D. This specifies a joint law and its implied test channel from X to $\widehat{X}$. Applying data processing to $X \to Y \to \widehat{X}$ yields $D \ge v\,2^{-2I(X;Y)}$. Multiplying the waveform by a unit conversion changes v and D together. A categorical estimate of a fall's direction needs its own loss and prior, so inserting it into the Gaussian formula would have no justification. [I1, I4]

A bound on reconstruction from physical remains

Let two admissible collapse histories h_0, h_1 yield target waveforms w_0, w_1 at a nominated exterior location, separated by $\Delta = \|w_0 - w_1\|$ in an explicitly weighted signal norm. Let P_0, P_1 denote distributions of all *available surviving observations*, from soil deformation to camera pixels, conditional on each history and sampling design. Define $\mathrm{TV}(P_0, P_1) = \sup_A |P_0(A) - P_1(A)|$. For equal prior probabilities the minimum error for deciding the history equals $(1 - \mathrm{TV})/2$. This follows by choosing hypothesis one on the set where its density exceeds that of zero, using the sum of the two laws as a common dominating measure. [I2]

Paired-history consequence. For any estimate of the target waveform from those observations, the equal-prior expected squared error is at least

$$\frac{\Delta^2}{4}\left[1 - \mathrm{TV}(P_0, P_1)\right].$$

For each observation y, both hypotheses share density at least $\min(p_0(y), p_1(y))$. In a Hilbert signal space, the sum of squared distances from any estimate to the two targets is at least $\Delta^2/2$; completing a square about their midpoint proves the inequality. Multiply by half the shared density and integrate, using $\int \min(p_0, p_1) = 1 - \mathrm{TV}$. Randomized estimators satisfy the same inequality after averaging over their auxiliary randomness. This is an elementary application of two-point decision theory to two *different acoustic histories with surviving traces* [I2]. It establishes no particular value of Δ or total variation in an actual wood. With identical residual laws the midpoint estimate attains $\Delta^2/4$ for this pair. With disjoint laws the bound falls to zero, as it must. For a larger history class its minimax squared risk is at least this two-point Bayes risk whenever both histories belong to the class.

For a concrete model, suppose lasting deformation depends only on delivered impulse magnitude, while the order of two airborne fracture pulses changes their waveform. Set the residual measurement equal in law under both temporal orderings and choose any two distinct pulse shapes with the same integrated mechanical proxy. Surveying the physical scar under this model leaves a positive lower bound for reconstructing temporal order. A synchronized remote recording sensitive to that order changes P_i, potentially removing the obstruction. The example is a non-identifiability construction. Its simplification makes no empirical assertion that any particular pair of trunks leaves identical microscopic states. Finite sampling and noise often provide the more relevant criterion of overlapping laws.

Soil displacement can constrain the interaction region; a broken branch can constrain loading and travel direction under a mechanical model. A neighboring tree's vibration can constrain arrival times only while the vibration persists or if a transducer stores it. Surface warming after friction can indicate dissipation yet admits alternatives such as sunlight. A photograph of the fallen geometry can survive long after propagating pressure disturbances leave the site. These are channels with different causal paths. In particular, a Markov chain from airborne field to *all* residual evidence generally fails. A stump and an acoustic pulse can share a mechanical cause, with the stump inheriting information

absent from the pulse. Data processing applies along each asserted chain, never merely because evidence was examined later.

Represent residual fragments by $R_1, \ldots, R_m$. The chain rule gives $I(X; R_{1:m}) = \sum_i I(X; R_i \mid R_{1:i-1})$. Ten exact copies of the same bit contribute its entropy just once; fragments carrying independent conditional noise can increase confidence. Conversely, two independent fair bits whose exclusive-or is X tell the reader nothing about X separately while determining it jointly. This guards against equating redundancy, number of physical imprints and information accessible from *any one* fragment. Laboratory questions include how many disjoint subsets maintain a predetermined error rate, over what interval, and under which access constraints. Strong claims about durable storage require these quantities or measured surrogates.

Algorithmic information concerns the shortest program for a finite symbol string on a specified universal machine. It relates to description length for one record and is generally uncomputable. A compressed file size gives an upper description-length estimate when the decoder, acquisition schema and other required information are included. Random microphone noise can enlarge a file and degrade inference about the tree. Conversely, nearly periodic ringing can be succinct to describe while carrying a sharply measured parameter. Entropy, code length, environmental correlation and useful inference require distinct bookkeeping. Under an ensemble of distinguishable alternatives a never-sampled field can carry positive information about what occurred, while a field the tree physically produced can carry zero information about a parameter to which selected coordinates are insensitive. [I1, I5]

7. Dissipation, entropy, and the lifetime of a sound

The fate of an acoustic joule

The energy that crosses an enclosing surface as airborne radiation is a transfer measured at that surface. A portion can subsequently become heat in the air, enter soil or vegetation, or escape the region being studied. Calling it both radiation and heat in the same final-state budget counts one transfer twice. Consider instead a clocked control volume. During collapse it receives work from moving solids. It temporarily stores organized compression and particle motion, exports a flux, and converts some of that organized energy internally. At a later epoch the outgoing pulse is elsewhere and absorbed energy contributes to the internal energies of many bodies. Each budget uses a time, a boundary and a convention for heat and work. Geometrical spreading reduces energy *density* at a point even when the integrated flux through complete spheres remains constant.

The second-order acoustic energy density for small isentropic perturbations in a uniform medium at rest is $e_a = |p'|^2/(2\rho_0 c_s^2) + \rho_0|\mathbf{u}'|^2/2$. Its flux to this order is $p'\mathbf{u}'$. Each density term has dimensions $\mathrm{J\,m^{-3}}$. In a uniform lossless fluid, multiplying linearized momentum balance by velocity and pressure evolution by $p'/(\rho_0 c_s^2)$ and adding gives $\partial_t e_a + \nabla\cdot(p'\mathbf{u}') = 0$ away from sources. Integrating over a fixed volume separates escape across a boundary from changes in local energy. Thermoviscous and other loss mechanisms modify this approximate balance. In a forest with incoming background sound a source-attributable budget requires either a paired baseline field or an identified source term. Squaring total pressure and subtracting baseline intensity without averaging or controlling phase can leave interference terms of either sign.

For a simple compressible Newtonian fluid with Fourier heat conduction, introduce absolute temperature T, specific entropy s, shear viscosity η, bulk viscosity ζ, thermal conductivity κ, heat flux $\mathbf{q} = -\kappa\nabla T$, and deviatoric strain-rate tensor $D' = (\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathsf{T}})/2 - (\nabla\cdot\mathbf{u})I/3$. Under local thermodynamic equilibrium the entropy balance reads [I6]

$$\partial_t(\rho s) + \nabla\cdot(\rho s\mathbf{u} + \mathbf{q}/T) = \frac{2\eta D' : D' + \zeta(\nabla\cdot\mathbf{u})^2}{T} + \frac{\kappa|\nabla T|^2}{T^2}.$$

The colon between tensors denotes componentwise double contraction. The right-hand side is nonnegative for nonnegative transport coefficients and has units $\mathrm{W\,m^{-3}\,K^{-1}}$. To derive the signs, substitute the internal-energy balance $\rho D_t e = -p\nabla\cdot\mathbf{u} + \tau : \nabla\mathbf{u} - \nabla\cdot\mathbf{q}$ in $Tds = de + p\,d(1/\rho)$. The continuity equation cancels pressure work and the divergence theorem moves transported entropy to the left. This identity holds for the total flow. Around an equilibrium background, weak-wave gradients generate second-order production. Subtracting two different *nonequilibrium* total productions need not leave an everywhere positive difference. Real air also exchanges energy among molecular degrees of freedom with finite relaxation times. Quantitative atmospheric absorption depends on composition, frequency and thermodynamic state. The simple closure explains the sign of dissipation without supplying an absorption coefficient for every forest. [I7]

For a historical packet whose unidirectional plane-wave amplitude attenuates as

$\exp(-\alpha x)$ at fixed frequency, its intensity attenuates as $\exp(-2\alpha x)$. If a layer of thickness L has no reflection, scattering or mode conversion, the lost flux fraction is $1-\exp(-2\alpha L)$. The expression distinguishes amplitude attenuation in inverse metres from a decibel rate. For a real reflection or scattering measurement, lost direct-path intensity includes energy redistributed into other paths. Extracting true heat production from that loss requires energy accounting on additional surfaces or independent material properties. Acoustic shadows and diminished coherent first arrivals alone do not establish enhanced entropy production.

The instant when the sound ends

At a fixed point a compact three-dimensional lossless free-space pulse can leave the point entirely after a finite time. The pulse can still be propagating beyond it. In a finite-dimensional damped mode with envelope $a(t) = a_0 e^{-\Gamma t}$, $\Gamma > 0$, mathematical extinction occurs only asymptotically. A threshold $a_* > 0$ is crossed at $\Gamma^{-1} \ln(a_0/a_*)$ when $a_0 > a_*$. In a reverberant medium, delayed arrivals can send a local amplitude back above that threshold. A more useful operational lifetime is then the end of the last above-threshold analysis window in a defined observation period. Infinitely many background-only windows with positive false-alarm probability make a naive last crossing a poor clock. The measurement rule must specify its false positives, its window and whether it tracks a source-specific template. There is no unique model-independent sharp time at which the event stops having made sound.

Fluctuation-dissipation analysis shows why adding detector gain alone cannot provide unlimited access. In a linear dissipative system near thermal equilibrium, fluctuations in generalized forces are related to dissipative response. Callen and Welton explicitly treated gas pressure fluctuations and acoustic radiation impedance [I8]. The measured pressure-noise spectrum depends on receiving area, response, dissipation, temperature and bandwidth. A single universal pressure threshold for the atmosphere would omit those variables. Natural forest noise, including wind and rainfall, is often far from equilibrium. The fluctuation-dissipation relation cannot assign a background spectrum to a storm. For one isolated classical harmonic coordinate in equilibrium, the Boltzmann distribution gives mean energy $k_B T$ across its kinetic and potential quadratures. That equilibrium scale provides neither a universal detectable point-source energy nor a sharp cutoff below which a signal cannot exist. Averaging repeated, phase-locked experiments can identify a small mean shift relative to individual fluctuations. One unrepeated unknown waveform offers different information.

A simple model makes the loss of accessibility precise. A phase-referenced mode coordinate after emission evolves as an Ornstein–Uhlenbeck process with relaxation rate Γ in equilibrium noise. Prepare stationary variance v under both hypotheses and means 0 and a_0. Independent thermal driving preserves the common variance while the separation of means becomes $a_0 e^{-\Gamma t}$. Under the assumptions of the Gaussian detection calculation, $d(t) = |a_0| e^{-\Gamma t}/\sqrt{v}$. For equal priors the optimal single-sample error approaches $1/2$ continuously. A finite positive amplitude makes the two finite-time laws distinct in this model; in a remote region behind a finite propagation front, identical local trajectories can in-

stead occur before arrival. Having an accessible mode with distinct laws at every finite time is a model result. It does not establish that a particular forest coordinate remembers the falling tree indefinitely under realistic access and sampling. A stored earlier time series changes the experiment.

The arrow of time and microscopic memory

Reversible microscopic models and irreversible macroscopic closures track different variables. In an isolated Hamiltonian model a bijective trajectory map preserves fine-grained distinguishability of full phase-space distributions and preserves phase-space volume. In ideal unitary quantum evolution the joint von Neumann entropy is invariant. Integrating out molecules, restricting to a microphone band, averaging over a volume, or allowing escaping degrees of freedom to leave the accessible region can reduce distinguishability. An apparently exact equality of coarse output distributions can coexist with different full states. These formal properties require the assumed closed dynamics. They do not imply that a finite observer can specify all initial molecular coordinates or solve a stable acoustic inverse problem.

For example, a thermal spatial Fourier coefficient in homogeneous diffusion decays as $T_k(t) = T_k(0)e^{-\chi k^2 t}$, with χ in square metres per second. Inverting ideal exact values at finite time uses a nonzero multiplier, but observational errors grow on inversion as $e^{\chi k^2 t}$. No bounded inverse exists uniformly over arbitrarily large k at fixed $t > 0$. Positive diffusion is already a coarse, irreversible description, and distinct noiseless initial profiles may still have mathematically distinct later profiles under that description. Practical memory can disappear through ill-conditioning without the map possessing an exact null space. Conversely, an imposed spatial averaging kernel may annihilate an entire mode immediately. A record can be irrecoverable because information lies outside the access map, because available precision is insufficient, or because the relevant region exchanged matter and energy with unobserved surroundings. These mechanisms need different tests.

Time reversal in acoustics has a clear experimental meaning. An array can capture a wave and re-emit time-reversed signals to refocus energy in suitable media [I9]. Such a reversal supplies a deliberately prepared input, requires adequate aperture and bandwidth, and depends on the medium remaining sufficiently reciprocal and stable. It does not retrieve a vanished pressure history from one late thermometer reading. Fluctuation relations compare probabilities of specified forward and reverse trajectories in stochastic microscopically reversible dynamics under defined preparation and driving protocols [I10]. Applying a work or entropy-production relation to an entire tree requires a specified initial ensemble, protocol and reverse experiment. A general claim that the forest will spontaneously replay an acoustic event with calculable probability from its estimated heat omits the necessary conditions.

For a small organized energy increment degraded into heat in a large reservoir near a common temperature T_0, the reservoir entropy increment has scale Q/T_0 if it receives heat Q. A full entropy production calculation includes the source, transport, other reservoirs and the path by which heat is generated. Landauer's result concerns the thermo-

dynamic cost of logically irreversible operations on specified information-bearing states [I11]. Dividing all energy dissipated by a trunk by $k_B T \ln 2$ supplies no count of recorded, lost or encoded acoustic bits. The atmosphere can retain correlations in slowly evolving thermal, compositional or flow variables after conventional detection becomes impossible. Their evidential value depends on whether different candidate histories induce separable laws for those variables. No established result assigns those correlations a complete retrievable recording. The historical proposition concerns energy transfer when the tree fell, and survives both dispersal of the wave and later loss of access to its traces.

8. Classical emergence and the spacetime location of production

What quantization could change

An elastic normal mode whose linearized Hamiltonian is quadratic has a quantum oscillator description with energy levels $E_n = hf(n + 1/2)$. A phonon is one quantum of excitation of a specified collective mode. In a vibrating solid with identifiable modes this description can be useful. O'Connell and colleagues prepared and manipulated individual excitations in a suitably engineered mechanical resonator coupled to a quantum circuit [I12]. In a warm, open, inhomogeneous forest the modes and their lifetimes depend on scale and boundaries. A phonon in an ideal normal-mode decomposition of air or wood should never be identified with a particular molecule or one heard impact. For the hydrodynamic description itself, wavelengths must be sufficiently long and periods sufficiently large relative to microscopic collision scales. As gas density decreases the assumptions underlying collective sound propagation eventually fail.

An equilibrium oscillator at temperature T has mean occupation $\bar{n} = (\exp[hf/(k_B T)] - 1)^{-1}$, derived by summing the geometric Boltzmann distribution of level occupation. At illustrative $f = 1000\,\text{Hz}$ and $T = 293\,\text{K}$, $hf/(k_B T) \simeq 1.64\times10^{-10}$ and $\bar{n} \simeq 6.11\times10^{9}$, using exact SI values of h and k_B [I13]. This number concerns one equilibrium mode at a specified frequency. It neither measures radiation by a tree nor demonstrates coherent excitation. Many thermal quanta can produce a zero mean pressure. A classical excess pressure waveform instead corresponds to a driven mean or to field correlations conditioned on the physical event. A phase-randomized impulse ensemble can have zero unaligned mean pressure and positive excess second moment. At these thermal scales classical fluctuation estimates are ordinarily appropriate; low-temperature and high-frequency modes permit regimes where discreteness and quantum noise are detectable. No quantization argument imposes a biological threshold for energy transfer.

A simplified model of environment-induced decoherence makes its claim and limits explicit. For two distinguishable source alternatives write the joint state after an interaction as $a|0\rangle|E_0\rangle + b|1\rangle|E_1\rangle$. The system's reduced density matrix has off-diagonal element $ab^*\langle E_1|E_0\rangle$. If many initially independent fragments acquire conditional product states, the overlap is the product of their overlaps. A product of many factors each of magnitude moderately below one can suppress interference in local measurements. Entanglement and unrecovered environmental records can make classical stochastic histories an excellent effective description of accessible degrees of freedom. This calculation supplies neither an estimate of a particular forest's decoherence time nor a mechanism selecting one unique actual outcome in every interpretation. A diagonal reduced matrix can arise from entanglement in a globally pure state and differs in its global experimental implications from a fundamental probabilistic mixture. [I14, I15]

Different accounts specify what counts as an event in different ways. A Bohr-type account emphasizes an arrangement and a classically describable phenomenon, allowing operational predictions for instruments that couple to the pressure irrespective of whether a person is listening. "Copenhagen" covers more than one view, and stronger histor-

ical consciousness-dependent proposals should be attributed precisely [I16]. Everett's relative-state formulation retains unitary evolution. It permits effectively decohered histories with correlated macroscopic records without a new consciousness-triggered dynamics [I15, I17]. Relational quantum mechanics attributes values relative to interacting physical systems, with no privileged membership rule based on being human [I18]. A trunk and the air can interact even when the region contains no organism with an auditory system. The philosophical force of an *absolute* observer-independent state is different under this account from that of a repeatable relation between material systems.

Objective-collapse models such as the Ghirardi–Rimini–Weber proposal modify the dynamics through spontaneous localization [I19]. They can differ experimentally from exactly unitary evolution; a statement that every account above makes identical predictions in every imaginable experiment would be too strong. Their localization mechanism does not require a witness and is distinct from mechanical collapse of the tree. Quantum Darwinism studies the dissemination of information about selected system properties into multiple environmental fragments [I20]. Different investigators may then learn similar facts from separate fragments. Redundant imprints require appropriate dynamics and an accessible observable. A mere molecular interaction does not guarantee a durable, independently readable copy of an entire pressure waveform. This is a framework for studying shared records and classical objectivity, rather than a numerical estimate of redundancy in this forest.

Quantum considerations enter the scale of noise, the dynamics and interpretation of macroscopic records, and the distinction between local loss of coherence and global dynamics. They provide no established empirical requirement that a conscious creature initiate ordinary acoustic propagation. A sufficiently sensitive coupled resonator can measure a quantum of motion in its designed regime. That result supplies no reason to postpone production of a kilohertz pressure pulse in a wood until its subsequent observation. Testing whether the mainstream effective description suffices requires a specific departure with a measurable prediction and uncertainty budget. Merely removing people while leaving tree, air and boundary dynamics fixed supplies no such departure.

A source world tube and two signal cones

Designate a source world tube W, for example the moving trunk and a proximate air shell, during the fall interval. Branch fractures, air displacement and impact occur at different positions and times. Calling the whole collapse an event is a spatial and temporal coarse-graining. For a source point at rest in homogeneous still air emitting at time t_s, lossless acoustics permits influence at distance r no earlier than $t_s + r/c_s$. Electromagnetic information travelling in vacuum can reach the same distance at $t_s + r/c_0$, where c_0 is the invariant speed of light. For $r = 100$ m and illustrative medium speed $c_s = 343$ m/s these delays are approximately 0.292 s and 0.334 microseconds. The latter is an ideal lower time for a light path and excludes camera exposure, optical propagation in matter, processing and decision time. At any observation point integrate retarded contributions from the entire source world tube. Apparent onset changes if a nearer branch starts later than a distant branch.

In a locally uniform, slowly varying moving fluid, the inviscid acoustic dispersion relation at leading order is $(\omega - \mathbf{v}\cdot\mathbf{k})^2 = c_s^2|\mathbf{k}|^2$. The two families of rays therefore travel, to the nonrelativistic accuracy of the model, with group velocities $\mathbf{v} \pm c_s\mathbf{k}/|\mathbf{k}|$. Refraction bends the effective acoustic cone. Solids and fluids can also supply distinct, path-dependent causal channels with different wave speeds. In a coupled earth-air problem an elastic disturbance can travel along the ground and later reradiate into air, so an arrival earlier than the predicted all-air path need not involve superluminal travel. The acoustic spacetime construction for suitable inviscid, irrotational, barotropic backgrounds identifies characteristics of perturbations; its metric does not replace the causal geometry of spacetime [I21]. Diffusion and certain approximate dissipative closures have mathematical tails at arbitrary distances immediately after forcing. Taking such tails as physically usable signals outside the light cone extrapolates the continuum closure past its domain.

Special relativity distinguishes disagreement about distant simultaneity from disagreement about the order of causally related events [I22]. On an acoustic ray in still air with spatial separation r, the relativistic invariant interval in the sign convention used here is $c_0^2\Delta t^2 - r^2 = r^2[(c_0/c_s)^2 - 1] > 0$. The endpoints are timelike separated. Every future-oriented inertial observer agrees that emission preceded reception, even though arrival delays and frequencies depend on relative motion. Two reception events at different locations can be spacelike relative to each other. Differently moving observers can assign them opposite coordinate order without disagreeing about which emissions caused them. The assertion “it has made a sound by now” requires identifying whose spacelike slice “now” denotes or specifying a local event on a world line. A distant receiver can also simply lack information that has reached a nearer one. This latter difference occurs even between clocks synchronized and at rest in one frame.

A physically defined source test avoids both ambiguities. Specify a material enclosing surface with an orientation and a duration marked by local clocks; choose a local rest frame tied to the background medium, an outgoing-wave prescription and a source baseline. Ask whether the source-attributable outward radiative energy evaluated there is positive. Coordinates can be changed while referring to the same material surface, same medium and same experiment. Numerical time components of a stress-energy flux or acoustic frequencies need not be invariant under arbitrary changes of physical observer. The proposition is invariant under *redescription of the specified procedure*. Removing a later listener outside the source’s past domain of dependence cannot alter that procedure’s outcome through a causal signal from the listener. A nearby microphone that changes acoustic loading supplies a different material boundary and a potentially different source solution. A receiver’s distance and elapsed travel time govern which claims it can establish; the existence of source work in its earlier world tube has its own local conditions.

9. The historical question and the logic of making a sound

What the historical evidence establishes

Aristotle's *De Anima* distinguishes capacities for sounding from actual sounding and discusses impact, air and hearing in Book II.8. Book III.2 relates the exercise of a perceptual capacity to the activity of the sensible object [O15]. The conjunction matters. The first passage investigates how sounding occurs; the second considers the unity of activity in actual perception. Reading either as a modern claim about a detector's influence on radiated power would import quantities and experiments absent from the text. Locke's discussion of secondary qualities in Book II, chapter VIII of the *Essay* gives a further distinction. A power belonging to a body can produce an idea in someone while differing from the resulting idea [O16]. The distinction permits a body to have a power during an interval in which its power produces no sensation. Having that power does not say whether a particular fall exercised it under particular physical conditions.

Berkeley's *Principles of Human Knowledge* (1710) gives close conceptual antecedents. Section 3 links a sound in the sensory sense with its being heard, using the table in an unoccupied study to discuss possible and actual perception. Section 23 invites the reader to imagine trees in a park and books in a closet; Berkeley argues that imagining them already involves a thinker [O17]. Neither passage poses a falling tree's production of a sound as a forest puzzle. Berkeley distinguishes spirits from the ideas perceived by them and gives divine agency a central role. Translating this into a decibel threshold for divine audition would add a premise to both theology and acoustics. A forest containing no human and a universe stipulated to have no perceiving spirit whatsoever are importantly different hypotheses within his system.

A contemporary newspaper gives a firmer date than the frequently cited 1880s accounts. The *Eastern State Journal* of White Plains, New York, on 6 May 1853, page 1, column 4, reports a question about a tree falling unheard and whether it makes a noise. It says the *Rondout Courier* announced the matter for debate at the village lyceum, with participants named on both sides [O18]. This establishes circulation of a closely matching production question by that date. The wording uses *noise*, with no island or woodland restriction in the initial sentence. The digitized record also predates the June 1853 Vermont instance reported by Jonathan Lighter. Ben Zimmer provided the pointer to the White Plains page in a 2020 American Dialect Society list discussion [O19]. Locating an accessible earlier printing does not identify an inventor. The notice itself points to an earlier announcement.

The June 1883 *Chautauquan*, volume III, number 9, "Editor's Table," question 3, pp. 543–544, frames the location as an island and excludes human beings. Its answer reasons from the need for auditory sense organs [O20]. This reasoning tacitly strengthens the premise if other animals with ears are allowed on the island. The *Scientific American* of 5 April 1884, volume 50, number 14, p. 218, answers a reader's question about an uninhabited island. The answer accepts that the tree sets air vibrating and reserves sound in the stipulated sense for sensory recognition [O21]. The apparent paradox in this reply dissolves when vibration and sensation receive distinct predicate names. These primary documents establish variants, uses and answers at known times. None establishes when

the exact modern sentence first appeared. In particular, the evidence defeats the claim that a popular periodical in 1883 invented the underlying question.

The historical sequence is a reason to preserve the verb *make*. The 1853 formulation makes the absence of hearing explicit in the antecedent and nevertheless asks about an effect of the tree. Substituting the question whether anyone heard the fall would answer its limiting condition by repetition. Likewise the *Chautauquan* formulation asks about existence and *Scientific American* offers a distinction about production and recognition. The present analysis fixes the grammatical subject at the tree and varies what its putative product is. That choice lets us investigate sources, emissions, dispositions and experiences without attributing a single philosophy to everyone who repeated the question.

Where a sound would have to be

There are substantive alternatives even after setting aside a strictly phenomenal account. A *medial* account locates sound in a propagating disturbance. A *distal* account locates it in an event involving the sounding body or in a property of that event. A *proximal* account may concern a stimulus at the ear or an experience. These alternatives vary independently of whether their referents are physical. A proximal change of eardrum pressure is entirely physical and still requires the particular eardrum to exist. O’Callaghan develops a relational event theory placing the sound in a body’s event of disturbing a surrounding medium. Casati, Dokic and Di Bona survey this and competing property, wave, event and dispositional theories [O22, O23]. This monograph’s production predicates apply those distinctions. They claim no historical priority for separating them.

Two observers separated by a ridge can hear arrivals with different timbres at different times. The tree and ground interacted in one extended collapse. A distal account may count one sound-making event with many modes of access. A medial account may describe one propagating wavefield with several reflected or refracted components. A phenomenal account may count two experiences even if both give exactly the same description. There are criteria of individuation within each account too. One can split the collapse into root failure, branch contact and stem impact, or treat it as a source episode lasting through all three. No disagreement about emitted energy is required for a disagreement about whether there were three sounds or one. Counting sound tokens requires an event-segmentation convention, particularly when the pressure contributions overlap.

This matters for measurement. Under linear propagation suppose two branches produce pressure histories p_1, p_2 at a microphone. The total squared pressure integrated over a time window includes a cross term $2 \int p_1 p_2 \, dt$. If those arrivals are coherent, summing the two isolated squared-pressure integrals gives a different value from integrating the actual squared pressure. This mathematical fact defeats a tempting identification of “one audible event per energy parcel.” A segmentation suitable for classifying sources and one suited to predicting local exposure can legitimately disagree. Complete cancellation at that microphone is compatible with two sound-making causes under a distal reading. It is also compatible with radiation to other places under a medial reading. The thought

experiment supplies no basis for inferring complete cancellation everywhere.

Predication, causation and quantifier scope

Let e be the selected collapse, B the event region including the physically relevant propagation window, and Y a class of products. Write $M_Y(e)$ when some token y of type Y occurs and its production is attributable to e through a specified path. For Y an emitted acoustic field, a direct mechanical source term and forward solution give that path. For a sensory effect, it runs through a biological receiver. For a replayed experience, the chain includes recording, storage, playback and a listener. The time interval matters: replay tomorrow cannot satisfy a claim about an experience in the forest today. A classifier label produced by accidental electronic noise is a token of the desired label type and fails the attribution requirement. The second half of the definition is indispensable.

“Nobody is around to hear it” admits a spatial, dispositional and actual-event reading. Define $\mathcal{H}$ as a domain of potential subjects, J as a time interval, Z as a spatial region, and $\mathrm{In}(h, Z, J)$ as occupancy during the relevant portion of J. One strong premise is that no member of $\mathcal{H}$ occupies Z in J. A weaker premise is that no occupant would detect this signal in these conditions. A different premise is that no occupant actually hears it. If the radiating episode and candidate hearing events have been restricted appropriately, the first implies absence of local experiences *in the chosen domain*. It does not assert global silence or exclude a receiver downwind outside Z. Someone can be present and fail to detect a sound. Someone initially outside the clearing can hear a delayed arrival. The time by which anyone has heard something must include the candidate reception time, or the absence claim may be trivially true before the first wavefront arrives.

The distinction between existential, generic and universal readings changes what a counterexample proves. A generic question asks what an ordinary collapse in a forest does under ordinary physical conditions. A universal question ranges over every admissible tree, atmosphere, impact and observer configuration. An existential question asks for any case in which a tree can make the specified sort of sound without a hearer. One radiating simulation in a clearly declared source model witnesses model consistency, and neither proves a universal theorem about real trees nor measures the typical proportion of all collapses that radiate. A vacuum case defeats a broadened universal about airborne waves even as a formal limiting case. It leaves the ordinary forest generic untouched because it changes the medium essential to that reading. Unless the domain and measure are known, terms like “usually” denote a qualified physical expectation, not a fitted frequency.

For explicit entailments, let G mean that the tree produced an identifiable physical acoustic component in the air in B, with identifiability here meaning causal specification in the model. Let D mean that an actual receiver correctly detected *that component*, P that someone experienced an auditory episode evoked by it, and $K_a G$ that agent a knows G. Let $\Diamond_{\mathcal{I}} D$ assert detection in at least one admissible instrument intervention in class $\mathcal{I}$, and let $J_{\mathcal{E}}(G)$ be the existence of sufficient later evidence under a stated inferential standard using evidence set $\mathcal{E}$. The following implications and failures are logical consequences of these definitions and the specified examples.

Relation	Status and reason
$D \Rightarrow G$	Valid for a veridical, causally attributed detection; a positive alarm has no such entailment
$P \Rightarrow G$	Valid for the event-specific *airborne*-evoked relation; generic auditory imagery can occur with G false
$K_a G \Rightarrow G$	Valid under factive knowledge; high posterior probability and confident belief are not factive
$G \Rightarrow D$	Invalid in an uninstrumented region, or when all accessible channels are insensitive
$G \Rightarrow P$	Invalid when no subject of the chosen type receives and experiences that component
$D \Rightarrow P$	Invalid for an unattended logger, even when later inspection establishes a genuine registration
$P \Rightarrow K_a G$	Invalid for an experiencer who cannot identify what made the sound and for an unrelated agent
$K_a G \Rightarrow D$	Invalid if an agent can establish emission by other evidence and a validated physical inference
$\Diamond_{\mathcal{J}} D \Rightarrow D$	Invalid when the admissible instrument was never deployed
$G \Rightarrow J_{\mathcal{E}}(G)$	Invalid when the accessible late evidence has the same distribution under credible alternatives

"Could have been heard" requires care even after adding modality. If $\mathcal{J}$ permits replacing the entire atmosphere, moving the tree, installing an amplifier and training a listener, the resulting test concerns a substantially different situation. Restrict $\mathcal{J}$ to interventions preserving the source, path and a specified back-action tolerance, and select permissible detector classes, false alarms and detection probabilities. A mathematical observer with access to the entire noise realization is a different resource from one ideal pressure transducer at a finite location. A physically radiating event can fail to be detectable in every admissible intervention in a narrow class. Enlarging that class can change the modal verdict without affecting the actual fall at all.

A corresponding distinction applies to the epistemic operator. Knowing that some sound was made requires weaker evidence than knowing its pressure at a prescribed location and time. A damaged tree and a photographed change in position can support a fall hypothesis while leaving impact speed, time, source spectrum and source/environment partition uncertain. A person hearing a transient can know that something happened without knowing that a tree caused it. A later investigator can know more about the source by combining traces than the person who heard the transient. To represent the stronger question, replace G with a proposition specifying the unknown and its tolerance. Being an earwitness alone is insufficient for detailed waveform reconstruction.

What metaphysical differences survive the measurement?

Scientific realism takes the existence of the theoretical entities posited by successful science seriously, with familiar debates over how far such commitment extends [O24]. Under an ordinary realist wave interpretation the tree's air disturbance can be real in the absence of any investigator. Direct realism about perception is a different thesis. One may hold that a conscious listener perceptually encounters a public sounding event while recognizing all the causal mediation supplied by the ear and nervous system. Indirect realist views distinguish an immediate perceptual intermediary from its external cause. They too can admit public sound-producing events. Directness of perceptual acquaintance and independence of the thing encountered answer different questions [O25]. A headphone experiment cannot decide between philosophical accounts that predict identical pressure traces, actions and reports.

Physicalism is a commitment concerning the physical constitution or determination of phenomena; by itself it does not select a use of the word *sound*. A physicalist can treat a vibration as a sound and an auditory experience as a distinct physical biological occurrence. The same thinker can reserve the term for the latter. An idealist of Berkeley's kind rejects a mind-independent material substance in the philosophical sense at issue, while allowing the regular course of sensory events and differences between individual observers. A universe without any minds challenges that theory's starting conditions. It does not follow that a human visitor must be present for regularities among ordinary things to obtain. Neither philosophical doctrine yields a new prediction about microphone response without further commitments [O17, O24, O25].

Phenomenalism involving standing possibilities of sensation distinguishes possible experience from presently occurring sensation. Mill's treatment of the enduring possibilities associated with matter is a historical example [O26]. On a specified counterfactual reading the unoccupied source can retain its disposition to affect an appropriately situated listener despite no manifestation on this occasion. To decide which possibilities count, one must state admissible circumstances. If the only admissible listener is a nearby human with no sensitivity in the relevant band, the corresponding disposition claim may fail. A criterion allowing another species or frequency translation tests another disposition. This is why an existence claim reduced to unspecified possible observation cannot supply a quantitative prediction.

An operationalist treatment ties the meaning of a quantity to specified operations [O27]. An unattended instrument can perform an operation and return a trace. An unperformed measurement can leave a numerical outcome undetermined in the archive while a validated model supplies a counterfactual prediction. A strong doctrine identifying meaningful assertions with actual readings would exclude some retrodictions. That is a philosophical decision extending beyond the practical norm that a measurement report must identify its procedure. A physicalist, realist and operational experimentalist can all agree on the contents of a file with undetectable signal while assigning different significance to the question of existence.

The empirically discriminating claims in this discussion concern interventions. Does changing storage leave radiated pressure invariant within uncertainty? Does holding

the input constant while changing attention alter a task score? Does rotating the receiver resolve interference that defeated the first orientation? The remaining disagreements concern what the selected term designates, which counterfactual worlds one admits, or what warrants ontological commitment beyond data. Separating these questions preserves a precise positive claim about what a tree makes while leaving open the questions that a measurement cannot answer.

10. Changing the conditions of production

The generic yes for an ordinary tree in air has physical prerequisites. To find them, vary one condition while fixing others as far as the equations permit. The natural baseline is an exposed terrestrial tree undergoing a finite-time mechanical collapse in a compressible atmosphere, with at least one unbalanced radiating component and no subject present to hear it. Cases that introduce a particular observer explicitly replace the absence condition for that observer. A strict vacuum, an ideal absorber and an exact quasistatic limit are model boundaries. None can be substituted silently for an ordinary wood.

Media and boundary conditions

Vacuum. Remove the gas from the open region surrounding the source. There is no airborne pressure degree of freedom there, so the answer to the airborne production question is no. The trunk and soil can still support elastic disturbances. A pressure gauge on the far side of the vacuum and an accelerometer bonded to the stem implement different experiments. If the wood outgasses, carries trapped air or ejects material, the assumed vacuum can fail locally. An actual vacuum tank can approximate removal of gas over a specified pressure range. The exact limit distinguishes kinds of media; it is not a proposal for growing an ordinary forest with no atmosphere.

Underwater. A flooded stand can contain submerged trees and a collapsing stem can load water. An outgoing waterborne disturbance then satisfies the same broad propagating-mechanical definition. For the same prescribed small normal velocity, the radiation impedance depends on fluid properties and geometry. For the same falling body, buoyancy, drag, added mass, and the density and prior waterlogging of the wood also change the trajectory. Equating a fall in water to the atmospheric fall with only the speed of sound replaced would mix two interventions. Airborne radiation is a separate question. It depends on interfaces, surface motion and transmission into air. A fully submerged fall in an unbounded-water idealization requires no atmospheric branch.

Perfect absorption. A nonreflecting enclosure filled with air supports outgoing waves from a source while allowing their energy to leave the domain. A perfectly matched boundary at finite radius terminates a computational domain. An enclosing absorbing material converts part of a crossing wave's energy internally. Neither construction deletes the field on its route from the source to the boundary. A claim about zero energy beyond a wall can thus coexist with positive emission measured inside. If an ideal loss mechanism is imposed everywhere, including the source, one must solve a different source-loading problem and specify whether any mode remains propagative. Assigning zero transmission to every receiver path without specifying such a model gives no source boundary condition.

Progressively rarer gas. In continuum linear acoustics and at fixed temperature for an ideal gas, $c^2 = \gamma p_0/\rho_0$ can remain nearly constant as density falls. The impedance $Z = \rho_0 c$ falls. For a prescribed locally plane progressive velocity, $p' = Zu$ and $I = Zu^2$ for rms velocity. Pressure and intensity then decrease, despite a roughly unchanged propagation speed. A fixed-force source produces a different limit because its velocity can increase or

its mechanical loading can shift to other paths. For a spatially compact source, radiation efficiency also depends on its dimension relative to the wavelength. Finally the molecular mean free path can become comparable to geometric or wavelength scales. Extrapolating a continuum sound wave all the way into the collisionless regime is unjustified. A rare molecule carrying momentum to a sensor is evidence of material interaction and need not constitute a propagating acoustic wave.

Changing the motion

Weak gravity. For a specified geometry and height change, the gravitational release is $Mg\Delta h$ and vanishes with g. Without external work or initial elastic energy, it bounds the sum of energy channels. A noiseless sensitive device might register a sufficiently small nonzero event at each positive g while the limiting radiated energy tends to zero. A model starting perfectly upright at rest also requires a perturbation or an initial tilt. If roots are strong enough to maintain equilibrium at low g, the stipulated fall never starts. At exactly zero gravity, the term “falls” requires imposed motion, prior momentum, or another force. Those replace gravity in the energy budget.

No contact with ground. A stem can become suspended by a neighboring crown. Breaking wood, moving leaves, and initial acceleration still offer acoustic channels before the catch. Contact with the canopy supplies its own force history. Alternatively consider a succession of models that end before ground contact. One can test whether the pre-impact motion radiated without saying what later happens. For a literally eternal fall at constant velocity through an infinite medium, a switch-on history, wake and reference state become essential. A steady subsonic ideal potential flow and a finite-time accelerating fall are different problems. The ordinary answer requires no single privileged instant called the impact.

Quasistatic descent. Slowing the same motion over a time T moves its spectrum toward low frequency and reduces its acceleration. For a compact dipole with fixed impulse and a smooth rescaled force history, the free-space dipole energy scales like T^{-3}; the assumptions include a fixed force impulse delivered to the air, not merely a fixed weight of wood. A controlled lowering apparatus can absorb nearly all the gravitational work. The limit $T \to \infty$ can approach radiative silence even though every member of a finite-time family radiates. The limit may cease to describe a completed fall in finite time. Zero lower bound and a positive minimum have different implications for a universal claim.

Perfect cushioning. A deep compliant bed can suppress high-frequency impact components. A perfectly inelastic stop concerns the final relative velocity; it says nothing by itself about the pressure waveform during deceleration. The bed must exchange momentum and can radiate. A highly elastic cushion can return stored energy in a slower rebound and still produce sound. A limiting passive or actively controlled cushion could redirect nearly all work into durable storage or heat. To infer silence one would have to establish the absence of radiating modes from all stages, including branch fracture and air displacement before impact. Specifying the final speed as zero only constrains a mechanical endpoint.

Changing access to the event

Masking noise. Add independent noise after the source is generated. If the medium stays linear and the tree mechanics are fixed, the coherent event component is unchanged. Its probability of detection in the mixture depends on receiver bandwidth, waveform knowledge, duration, noise covariance and false-alarm tolerance. A deeply buried waveform can remain statistically distinguishable even when a single trial yields no reliable classification. Conversely, wind noise acting on the tree as well as the detector is not an after-the-fact mask. It changes the joint source and noise law. A claim that a sufficiently loud background makes the tree literally emit nothing would require destructive modification of the source or a definition tied to access.

Outside a human passband. A sufficiently slow component belongs to the mechanical field even if no human ear is sensitive to it at the received level. A band restriction is operational and individual. A wideband, finite-duration transient cannot in general have both compact time support and an exact spectral gap extending through a whole open band unless its analytic Fourier transform is identically zero. Accordingly "entirely outside" can denote an ideal band-limited signal with temporal tails, or negligible in-band energy relative to a specified criterion. The realistic case is often the latter. The answer for a human receiver does not generalize to all other species or machines.

Unconscious or deaf observer. Physical proximity alone does not determine sensation. A fully stipulated absence of conscious auditory experience entails no such experience during the interval. Sleep, anesthesia and clinical unresponsiveness are more heterogeneous empirical conditions. Unresponsiveness alone cannot establish absence of all percepts. Deafness likewise varies with individual, band, amplification and route. Someone may detect floor vibration by touch. That gives a biological response attributable to the fall even when auditory perception is absent. No diagnosis is an adequate substitute for a defined modality and criterion. The sound the tree made in air can be identical across these receiver cases if source coupling is held fixed.

Recorder present, lost, or never played. An unattended microphone can transduce an attributable pressure signal. Storage additionally requires a functioning recorder. In ordinary usage it is an instrument and does not satisfy the condition "somebody is around." Destroying the stored file later does not alter earlier emission or earlier acquisition. The magnitude of the evidential loss depends on copies, independent sensors and remaining physical damage. A recording never played can support machine inference without ever producing an auditory sensation. A subsequent playback produces a new wave. Archive and playback belong on a causal chain with separate places and times.

Changing the possible world

No auditory organisms and no conscious observers. A stand without animals capable of auditory perception still contains living trees and other responding material. There is no logical inconsistency in the first scenario. Saying there are no organisms at all in a forest made of living trees would change the premise. A universe with material forests and no consciousness is a model counterfactual. Classical field equations admit a solu-

tion on the specified material data without a consciousness variable. That result neither verifies an actual, universally unobserved universe nor settles a theory on which physical reality is constituted by mind. The empirical question is whether adding a consciousness-dependent production rule yields independently testable predictions. The cited acoustic and measurement literature supplies no such necessity.

Ground-only detection. A particular field station can register strong elastic motion while a microphone fails. The two measurements have different couplings, noise distributions and geometry. Such evidence can establish motion even if it does not identify any historical airborne waveform. Replacing "the ground channel alone yielded a detection" with "only ground waves existed" changes an observation into an unsupported claim about the entire field. A physical setup with a vacuum around a resonating trunk is a distinct special case where the absence of the airborne branch follows from the medium.

No later evidence. Define an accessible algebra of observations: for example, surviving field notes, topography and instrument files at a certain time. Two histories can agree on every accessible observation while differing in their emitted pressure histories. The exact history can then be unrecoverable within that experiment. The stronger statement that observations cannot update prior odds requires identical likelihoods for all accessible outcomes under the competing hypotheses, including any pattern of missing records. A missing file can favor an event if event damage preferentially destroys the recorder. Making the stronger assertion that *no possible observer with access to any environmental degree of freedom anywhere* could distinguish the histories requires a model of global dynamics, boundary conditions and what counts as an observer. Local thermalization alone does not prove that. An unrecoverable pressure waveform can coexist with decisive evidence that a tree fell. The opposite combination is possible if a recorded impulse survives but the source identity is lost.

Verdict matrix

Each row concerns the specified collapse rather than unrelated ambient noise. "Ord." means yes under ordinary exposed finite-motion coupling; it makes no assertion of a measured population frequency. "Dep." means the scenario leaves essential facts unspecified. "None" in the experience column assumes that all eligible hearers are absent except for any observer specifically introduced by the row. "Possible" describes compatibility, not an actual observation. In the last column the target is a *later case for the event*, which is weaker than recovery of its complete waveform. The companion CSV extends the matrix to include separate artificial and biological transduction and the strength of the possible-world assumption.

Condition	Air wave	Other mechanical wave	Evoked experience	Recording or later evidence
Ordinary exposed collapse, nobody present	Ord.	Ord.	None	Independent traces possible
Ideal vacuum around tree	No	Possible in wood or soil	None	Solid sensor or damage possible

Condition	Air wave	Other mechanical wave	Evoked experience	Recording or later evidence
Submerged collapse	Dep. on interface	Ord. in water	None	Hydrophone or debris possible
Perfectly absorbing enclosure	Ord. inside	Dep.	None	Interior record possible
Decreasing air density	Dep. on regime and loading	Possible	None	Detector-specific
Extremely low gravity	Conditional on actual fall	Dep.	None	Independent traces possible
No ground impact	Ord. if other radiators active	Possible	None	Canopy or motion traces possible
Quasistatic descent	Can approach zero	Dep.	None	Position change can persist
Perfectly cushioned impact	Dep. on motion, cushion and other sources	Dep.	None	Motion traces possible
Masked by intense noise	Ord.	Ord.	None by premise	Detection test-dependent
Outside human audible band	Yes if acoustic	Dep.	None by premise	Band-matched detector possible
Unconscious observer	Ord.	Ord.	None if stipulated unconscious throughout	Physiological response possible
Deaf observer	Ord.	Ord.	Depends on subject, band and route	Tactile or instrumental evidence possible
Unattended microphone	Ord.	Ord.	None	Signal if coupled, record if stored
Recording later destroyed	Yes if attributable air record	Dep.	None	Earlier record existed; other evidence possible
No auditory organisms	Ord.	Ord.	None	Instrument or physical traces possible
Detected only through ground	Unknown from detections alone	Yes if attributable	None	Ground detection occurred; retention unspecified
Universe without conscious subjects	Ord. in stipulated physical model	Ord. in model	None	Physical records possible
No accessible later evidence	Dep. on physical history	Dep.	None by premise	No update if accessible data have identical likelihoods

The principal difference between the rows lies in what was changed. Removing a medium removes a production channel. Moving a microphone usually changes access. Erasing a file changes future evidence. Suspending the tree changes its motion. Those interventions cannot be exchanged merely because each can lead to the same entry in an investigator’s notebook. The source question must be answered in the world in which the specified intervention was actually made.

11. A numerical experiment on what the tree produces

Design and status of the evidence

A falling tree supplies a useful test for an acoustic model because neither the existence nor the magnitude of a pressure pulse should be inferred from the behavior of a microphone placed far away. The numerical experiment therefore starts at the tree, accounts for the work available to excite a disturbance, constructs an outgoing pressure field, and sends that field through two paths to an array of *virtual* receivers. Source coordinates, receiver coordinates and noise can be varied independently. The final experiments attempt to infer properties of the source from the receiving side alone. Every numerical result in this chapter comes from an executed synthetic experiment. The ranges in the companion repository are declared inputs. None is an empirical estimate of the fraction of a tree's energy radiated into the atmosphere.

Three levels of numerical claim will recur. The mechanical energy identity is a property of specified differential equations and can be verified against a separate calculation. The reduction of high-frequency content behind a strip is an outcome of imposing a particular lossy channel. The claim that a particular natural stand would produce the same reduction would require field data. Keeping the three levels distinct allows one to answer a physically interesting question even before the measurements exist. A positive source can be held exactly fixed during a change in detectability, and its emitted energy can be changed without solving a new detection problem. A model with its radiation efficiency set to a positive number supplies an example. It cannot establish a universal lower bound for every falling tree.

The input tree has length 18 m, mass 900 kg and a nominal drag diameter of 0.38 m. The mass includes everything lumped into the rotating rod, and the diameter enters only the projected-area model. There is no implied species, growth history or diameter-based biomass equation. The tree starts from rest at six degrees from the vertical. An initial tilt is necessary because an exactly upright rod released with exactly zero angular velocity at an ideal hinge remains an equilibrium of the deterministic equations. The gravitational acceleration is 9.81 m/s². The synthetic air has density 1.2 kg/m³ and sound speed 343 m/s. Those numbers and the dimensionless drag coefficient of one specify one test problem. They are retained at full precision in the configuration for numerical comparisons.

Gravity, drag and first contact

For a uniform rod hinged at its base the moment of inertia is $I = mL^2/3$. The tip speed is $v = L\dot{\theta}$, and gravitational torque about the hinge is $T \sin\theta$, with $T = mgL/2$. During outward rotation the velocity at distance s is $s\dot{\theta}$. Integrating the local drag force $\rho C_D D(s\dot{\theta})^2\, ds/2$ times its moment arm over the rod gives a resistive torque of magnitude $q\dot{\theta}^2$, where $q = \rho C_D D L^4/8$. Writing the signed equation as $I\ddot{\theta} = T\sin\theta - q\dot{\theta}|\dot{\theta}|$ also gives the correct drag sign if the motion reverses. First impact is the event $\theta = \pi/2$. Soil failure and the release mechanism lie upstream of the initial condition. The hinge supplies constraints, and in this surrogate its fixed point does no work. The model excludes

aerodynamic sound from the pre-impact drag energy.

The fixed-step fourth-order Runge–Kutta solver integrates angle, angular velocity and drag work simultaneously, with $\dot{W}_D = q|\dot{\theta}|^3$. Within the step containing first impact it solves for a fractional step length to place the final state at horizontal. Stopping at the first grid point beyond horizontal would incorporate a timing error dependent on the fraction of a step left over. That error could dominate convergence while leaving the underlying differential solver intact. The reference calculation changes the independent variable to angle. With $y = \dot{\theta}^2$ and $b = 2q/I$, the equation on the forward branch is $y' + by = (2T/I)\sin\theta$. If θ_0 is the starting angle,

$$y(\theta) = \frac{2T/I}{1+b^2}\left[b\sin\theta - \cos\theta - e^{-b(\theta-\theta_0)}(b\sin\theta_0 - \cos\theta_0)\right].$$

Reference fall time comes from the integral of $1/\sqrt{y}$ over angle. The substitution $\theta = \theta_0 + u^2$ regularizes the endpoint at release. In a second check the model sets drag to zero and compares terminal speed directly with the potential-energy drop. At the production step of 0.005 s the absolute difference from that no-drag angular speed is 2.95×10^{-12} rad/s. For the original drag case, decreasing the step from 0.16 to 0.08 to 0.04 s reduced absolute terminal-speed error from 2.93×10^{-6} to 1.82×10^{-7} to 1.14×10^{-8} rad/s. The ratios approximately equal sixteen, as expected for a smooth fourth-order method. They test an implementation of the stipulated torque law. They furnish no evidence that a crown with flexible, reconfiguring branches actually experiences that law.

The descent took 3.855505 s. The available gravitational energy was 79,025.70 J. Of that amount, 5,240.09 J was debited to drag work and 73,785.62 J reached the horizontal configuration as kinetic energy. The terminal angular speed was 1.232162 rad/s and the tip speed was 22.1789 m/s. The absolute energy-balance residual at the production step was 2.78×10^{-7} J. The separation between this residual and the size of the omitted physical mechanisms matters. Rounding the calculated impact energy to the nearest joule already overstates the predictive precision available for any actual specimen.

Immediately before contact, the kinetic energy can be expressed as $m_* v^2/2$ with the tip effective mass $m_* = I/L^2 = m/3$. During the short contact interval the model neglects gravitational work and replaces the entire distributed structure by this one mass, a spring with $k = 18$ MN/m, and a compression damper. Compression x is positive into the support. The reaction is $kx + d\max(\dot{x}, 0)$ until release at $x = 0$ on rebound. The dashpot acts only while compressing. Stored strain energy accelerates the outbound mass without a tensile contact force. This deliberate constitutive choice makes both positive work loss and energy return independently checkable. It supplies no species-specific estimate of stump stiffness, soil damping or coefficient of restitution.

Set $\omega_n = \sqrt{k/m_*}$, $\zeta = d/(2\sqrt{km_*})$ and $\omega_d = \omega_n\sqrt{1-\zeta^2}$. For the chosen underdamped compression with $\zeta = 0.28$, $x(t) = ve^{-\zeta\omega_n t}\sin(\omega_d t)/\omega_d$. The first maximum occurs at $t_c = \arccos\zeta/\omega_d$. After that instant, unloading takes one quarter of an undamped period. The model gives 62.21 mm of peak compression in 5.473 ms and 11.886 ms from contact to release. Spring return accounts for 34,827.68 J and the irreversible contact debit accounts for 38,957.94 J. Integrating the piecewise differential equation separately, with

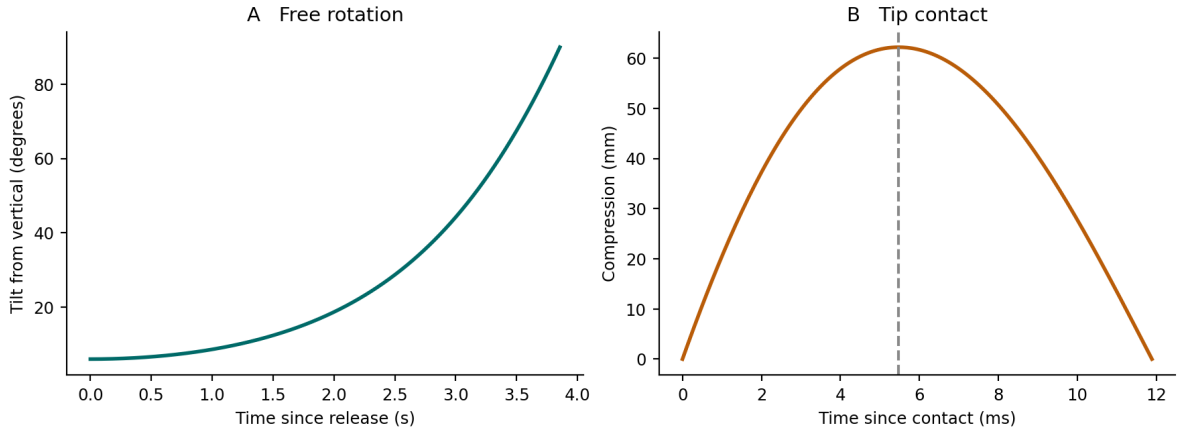

Figure 4: Free rotation of the synthetic tree and compression during a single tip contact. The dashed line marks the transition from loading to unloading.

adaptive time steps and a release event, gave a contact loss within 1.6×10^{-7} J and duration within 1.4×10^{-14} s of the formulas. The solution has no sustained rest phase. The rebound allocation is a balance at release, and its subsequent fate would require another model.

From mechanical debit to a pressure field

The source construction allocates a fraction η of contact loss to airborne radiation, represented by its free-space equivalent. This allocation is phenomenological. In particular, the one-degree-of-freedom dashpot is an effective sink. The calculation partitions its work among unresolved mechanisms and removes the allocated sound from the amount left for all the others. Counting both undiminished dashpot work and acoustic energy as separate final sinks would count the same work twice. For reference $\eta = 10^{-5}$, the constructed outgoing field carries 0.389579 J in free space. Changing η by a factor of 100 changes free-space energy by 100 and every pressure amplitude by ten. If $\eta = 0$ the constructed impact source is identically silent. That limiting calculation says nothing about omitted fracture, aerodynamic or ground-radiation sources.

Let T_c now denote total contact duration. A slow impulse has shape $g(u) = u\exp(-u^2/2)$ and scale $T_c/4$. A second copy of scale $T_c/24$ starts about a half-contact duration later in the sense of its central zero crossing, with relative weight 0.65. Each pulse has positive and negative phases and zero continuous-time integral. The Gaussian tails do not have compact support. The pulse reference locates a chosen waveform feature and does not date the first nonzero pressure sample. Two widths provide a minimal source for testing spectral distortion. They do not identify actual fractures, material resonances, or a frequency spectrum typical of trees.

Define $s(t)$ so that the outgoing progressive pressure at distance r in free space is $p(r,t) = s(t-r/c)/r$. The normalized coefficient obeys

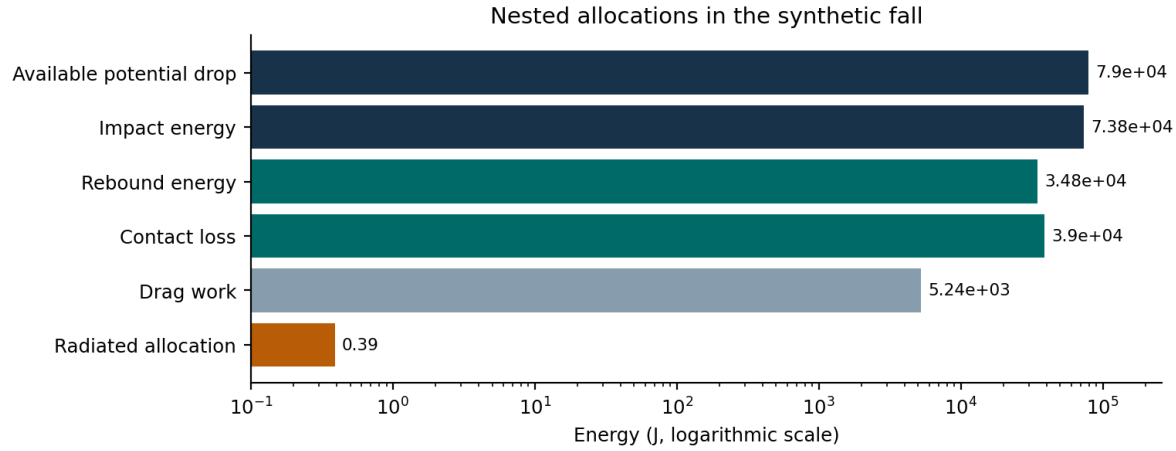

Figure 5: Energy terms at release. Bars occupy nested levels of a budget. Impact divides into rebound and contact loss, and radiation is a small allocation within the loss.

$$\frac{4\pi}{\rho c}\int s(t)^2\,dt = \eta E_{\mathrm{loss}}.$$

In SI units s has dimensions Pa m. Its numeric value equals the reference pressure extrapolated to a radius of one metre. The plotted coefficient is a spherical-wave reference, and the inner eight metres of the propagation maps are omitted. The integral gives the flux of an isolated outgoing source integrated over a full sphere. Ground reflection in the receiving calculation changes pressures near the ground. A model in which the surface also changes the source impedance would need to recompute the actual emitted power. A local pressure increase from interference does not establish an increase in free-space source energy.

The production rate is 4,096 samples per second in a one-second window. The one-sided DFT uses double multiplicity for interior frequencies and unit multiplicity at DC and the Nyquist frequency. Parseval’s identity recovered 0.389579 J from the spectrum. The largest energy bin was at 52 Hz. The frequencies at which cumulative energy first crossed 5%, 50% and 95% were 22, 59 and 259 Hz respectively. The band at and above 120 Hz contained 8.822% of source exposure. These statistics report a particular normalized pulse, including the interference of its two components. Assigning an arbitrary mean audible frequency to the gravitational energy would supply none of them.

A Green function that can be inspected

At each horizontal coordinate the response is the sum of a direct ray and an image ray from a planar ground surface. Source and receivers stand at 2.0 m and 1.2 m. A strip between east coordinates 23 and 46 m extends across the map. A ray of length ℓ has length ℓ_v within its vertical projection. Its complex gain is

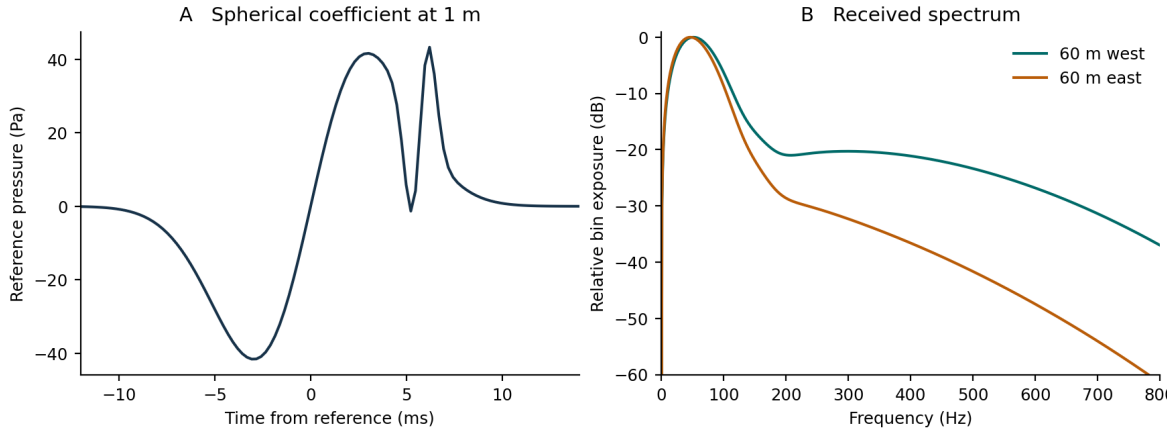

Figure 6: The two-component synthetic source and spectra at equal distances along open and strip-crossing rays. Each received spectrum is normalized by its own maximum for the shape comparison.

$$H_\ell(f) = \frac{1}{\ell}\exp[-b_0\ell - b_v\ell_v](1 + if/f_0)^{-a_0\ell - a_v\ell_v}\exp[-2\pi i f\ell/c].$$

The direct gain is combined with 0.55 times the reflected gain, using their respective travel distances. The constants are $b_0 = 0.00065$ and $b_v = 0.014$ Np/m, $a_0 = 0.0018$ and $a_v = 0.068$ per metre, and $f_0 = 125$ Hz. All are design parameters. The real exponential supplies grey pressure loss. For positive order a, the factor $(1 + if/f_0)^{-a}$ is the transform of a causal gamma impulse response with shape a and rate $2\pi f_0$. Its modulus attenuates high frequencies, while its phase imposes the associated delay. Orders from adjoining lengths add, so adding an extra length of identical statistically represented material has a consistent effect. Taking an arbitrary frequency-dependent attenuation with zero phase would generally forfeit this causal time-domain interpretation. The Green function here is a ray surrogate. Its parameters encompass unresolved attenuation effects and do not resolve individual stems, diffraction at a sharp ridge, stochastic scattering, a moving canopy or atmospheric inversions.

For one ray with all attenuation set to zero, the numerical modulus multiplied by path length equals unity to within 2.22×10^{-16}. An independent sampling check integrated the receiver pressure squared at 2,048, 4,096, 8,192 and 16,384 Hz, and doubled the window to two seconds. At the strip-crossing point 60 m east, exposure changed from 0.002750404 Pa² s at 2,048 Hz to 0.002750685 Pa² s at 4,096 Hz. The two-second 16,384 Hz calculation agreed with the production-rate independent calculation within numerical precision. Composite Simpson integration at 4,096 Hz differed from sample summation by approximately 2.9×10^{-11} Pa² s. These tests check numerical quadrature and finite-window effects for this particular disturbance. They do not eliminate modeling error or justify a 4,096 Hz sampling rate for the fracture of an unknown tree.

The maps show five different quantities. The first is RMS pressure over a fixed one-second record, obtained from pressure exposure divided by the window duration and

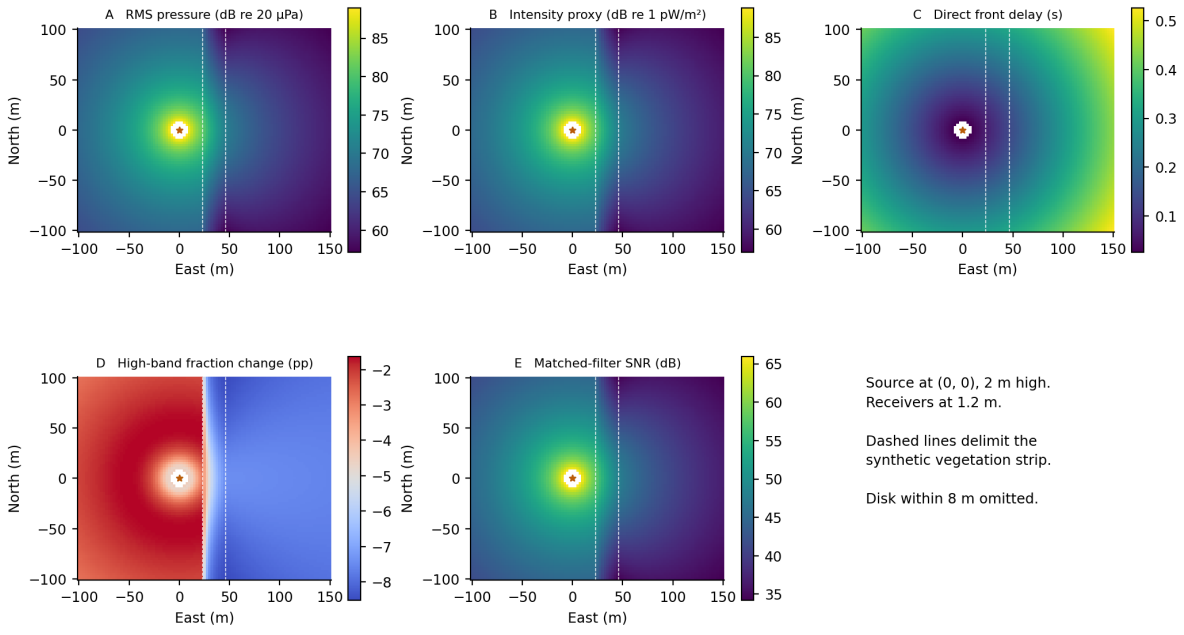

Figure 7: Pressure, progressive-wave-equivalent intensity, impulse-front delay, spectral redistribution and matched-template SNR for one explicitly synthetic site. The blank central disk excludes the near-source region.

square-rooted. The second is a plane-progressive-wave intensity equivalent, $p_{\mathrm{rms}}^2/(\rho c)$. A spatially varying two-ray field has a vector intensity $\langle p\mathbf{v}\rangle$. Consequently the second map cannot be integrated to infer the net energy through a surface. The third records the earliest geometrical delay of an impulsive input, namely direct path length divided by c; the smoother imposed pulse itself has no exact front. The fourth is the change in the proportion of pressure exposure above the chosen split. The fifth is the optimal known-template signal-to-noise ratio in dB, $10\log_{10} d'^2$, for the declared sampled noise. That ratio and the fixed-window pressure level answer different questions and have different reference conventions.

At 60 m east and west, direct arrival delay was 0.174943 s in both directions. Westward passage gave 0.00754028 Pa² s of exposure and 7.170% of it in the high band. The strip-crossing path gave 0.00275069 Pa² s and 1.360% in that band. The eastward energy-exposure deficit was 4.3795 dB. Identical source, range, receiver height and earliest geometric delay did not fix the received amplitude or spectrum. The model has no exactly silent shadow because all gains are finite, the reflection amplitude is limited, and the source has multiple frequencies. To classify a region as inaccessible one must give the receiver bandwidth, noise and decision rule. Reducing the postulated coupling or increasing noise can move the same point across such a threshold while leaving its geometrical arrival time unchanged.

Which assumptions control received energy?

Changing one input by a fixed percentage near a chosen operating point can conceal uncertainty in the form of the question itself. Here a distinct experiment asks which input accounts for the variance of *received energy fluence* if the investigator chooses to distribute eight independent design coordinates over specified ranges. Each design uses a fresh eight-dimensional vector for the tree and its path. For this experiment the channel has a direct ray with grey attenuation α in dB/m. The response is

$$Y = 10\log_{10}\left[\frac{\eta E_{\mathrm{loss}}}{4\pi r^2 F_{\mathrm{ref}}}\right] - \alpha r, \qquad F_{\mathrm{ref}} = 1\ \mathrm{J/m^2}.$$

This is a different output from a pressure level referenced to 20 µPa. The geometric factor gives incident fluence before path loss. The disjoint sensitivity experiment removes reflection and spectral filtering so that interactions between uncertainty in source energy, geometrical spreading and distance-dependent loss can be traced directly. Its absolute results should not be compared with the pressure maps without changing the models and units to match.

Mass and length are independently uniform over 400–1,600 kg and 12–24 m. Drag coefficient is uniform from 0.6 to 1.6. The base-ten logarithm of stiffness in N/m is uniform from 6.6 to 7.6. Damping ratio ranges from 0.08 to 0.50. The logarithm of η ranges uniformly from -8 to -3. Distance ranges from 50 to 300 m, and α from 0.001 to 0.05 dB/m. These independent ranges need not describe any population of trees. In particular an allometric relation would correlate mass, length and diameter; a measured frequency-dependent attenuation law would associate propagation with tree size through its emitted spectrum. The broad range of η deliberately asks what happens when mechanical-to-acoustic coupling is poorly constrained. It should never be used to bound natural values.

For independent inputs, the first-order index is $\mathrm{Var}(\mathbb{E}[Y|X_j])/\mathrm{Var}(Y)$ and the total index is $\mathbb{E}[\mathrm{Var}(Y|X_{-j})]/\mathrm{Var}(Y)$. The program used squared-difference estimators on pairs of independently parameterized points in a jointly scrambled 16-dimensional Sobol design [C1]. Each scramble supplied 4,096 base vectors, 4,096 companion vectors and their coordinate exchanges. Eight scrambles produced 32,768 base values and a between-scramble precision estimate. The central 95% design interval for Y was -97.78 to -39.74 dB re 1 J/m², with median -68.79 dB. A design interval describes the imposed input measure and simulation; it has no coverage interpretation for an unsampled real forest.

Radiation fraction accounted for a first-order share of 0.8115 and a total share of 0.8113. The slightly reversed ordering is Monte Carlo integration error; the population total cannot fall below the population first-order effect. Range had shares 0.1390 and 0.1429, and grey attenuation 0.0241 and 0.0279. Range and attenuation interact through their product. Mass had total share 0.0126 and damping ratio 0.0070. Contact stiffness had an effectively zero total share. The result for stiffness follows directly from the equations: $kx_{\mathrm{peak}}^2/2$ scales as $m_* v^2$ times a function of damping ratio only when ζ is held fixed. Changing k rescales contact time and changes the spectrum. A broadband, grey, energy-only metric is blind to that change. A band-limited sensor or a design that holds dimensional dashpot strength fixed would ask a different question and could yield a nonzero index.

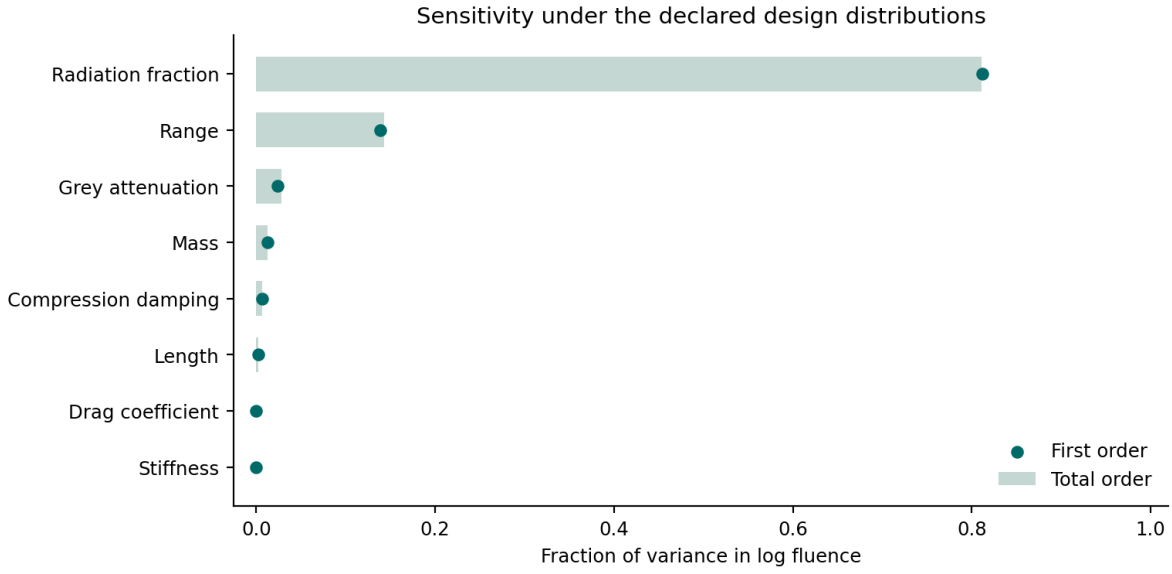

Figure 8: Variance fractions for the independent design inputs. Bars give total-order estimates and dots first-order estimates. The response is log fluence in the grey direct-path experiment.

There is an independent arithmetic test for the largest share. The term $10 \log_{10} \eta$ is independent of every other term in this particular output and is uniform over an interval of 50 dB. Its variance must therefore be $50^2/12$ square decibels. Its exact first and total shares must coincide. An independent implementation can compare this value with sample output variance without recomputing any conditional expectations. This check also explains why the numerical ranking should not be universalized. If the logarithmic range of the coupling were halved with all other inputs unchanged, its absolute contribution to variance would fall by a factor of four.

A receiver threshold and what lies below it

Let a processed record contain the known noiseless pressure sequence s plus independent zero-mean normal errors with variance σ^2. All records are synchronized and have a known gain. The statistic $z = \langle s, y \rangle / (\sigma \|s\|)$ is standard normal under the null, and normal with mean $d' = \|s\|/\sigma$ and unit variance when the event occurs. This follows by projecting a vector of independent normals onto a unit vector. The code uses the exact one-sided null quantile 2.32635 for a 1% false-alarm design. Its theoretical detection probability is $\Phi(d' - 2.32635)$. A 95% hit probability thus requires $d' \simeq 3.9712$. Finite positive pressure does not automatically give that degree of reliability. If a timing search scans many candidate windows, the false-alarm probability must apply to the entire search, or to a declared false-alarm rate, before extrapolating this threshold.

For each of seven values of d' the program generated 120,000 scalar normal trials of the projected statistic. At $d' = 0$, 1.034% exceeded the critical value. At $d' = 2$, 36.923% exceeded it, versus 37.208% analytically. At $d' = 3$, 75.071% exceeded it, versus 74.973% analytically. At $d' = 4$ the simulated and analytical values were 95.207% and 95.290%.

Monte Carlo estimates fluctuate. The per-condition 95% Wilson interval need not cover every analytical probability in a family of independent checks. A second implementation actually drew 4,000 full 4,096-sample records at $d' = 3$, performed the vector product, and registered 2,978 detections. Full-vector passage therefore gave 74.45%, close to the scalar simulation while exercising the detector's input representation.

The reference maps use a hypothetical discrete per-sample noise standard deviation of 0.018 Pa. Their high values of d' are conditional on knowing the exact template and alignment and on the chosen synthetic noise. Holding discrete variance fixed while raising sampling rate increases the effective information in a fixed-duration record by assumption. A physical receiver with fixed continuous spectral noise density requires an appropriate noise bandwidth and sampling convention. No inference about a human hearing threshold follows from the map or these digital trials. Most importantly, the threshold appears in the receiving experiment. The model computed the source work before any receiver or noise draw existed in the calculation.

Inferring emission from imperfect records

The inverse experiment introduces two unknowns while holding the mechanical reference and receiver geometry fixed. The first is $e = \log_{10}(E/E_0)$, which scales pressure by $10^{e/2}$. The second is a nonnegative extra dimensionless filter order a along the entire path, multiplying the known channel by $(1 + if/f_0)^{-a}$. A receiver 68 m east and 6 m north of the source receives a synthetic event with $e = 0.22$ and $a = 0.85$. Its noise is chosen to give $d' = 24$ for the true waveform, corresponding to 0.145455 Pa standard deviation per sample. The inference experiment deliberately differs from the reference map noise setting. The two unknowns represent real competing explanations for a quiet record: smaller source energy and greater path loss. The model treats the arrival timing, source shape, reflection coefficient, baseline medium and the noise distribution as known.

Two observation schemes use the same simulated pressure record. One retains only the magnitude of its 80 Hz Fourier coefficient. Because real and imaginary Gaussian noise components have equal variance, integrating the two-dimensional normal density over phase produces the Rice likelihood in this scheme [C2]. Frequency is fixed, and expected magnitude depends on the product of a source scale and a path modulus. Exact knowledge of that one magnitude would identify only the product. The second scheme retains both quadratures in positive DFT bins from 10 through 700 Hz. The known pulse and frequency-dependent complex gain vary across the band. Phase can constrain attenuation order in this toy channel because the emission reference and propagation delay have been supplied. In field applications an unknown clock offset, an alternative pulse shape, or dispersive multipath could consume some of that information.

Independent uniform priors span $-0.6 \le e \le 0.9$ and $0 \le a \le 2.1$. Posterior masses are computed on a 151 by 141 grid, using boundary trapezoidal weights and a Gaussian likelihood for the interior complex bins. With a one-second window and the DFT convention in the repository, each interior real or imaginary noise coefficient has variance $N\sigma^2/2$. Using the time-domain variance in its place would concentrate the posterior spuriously. The MAP coordinate for the complex-bin analysis was $(0.18, 0.945)$. The posterior median for

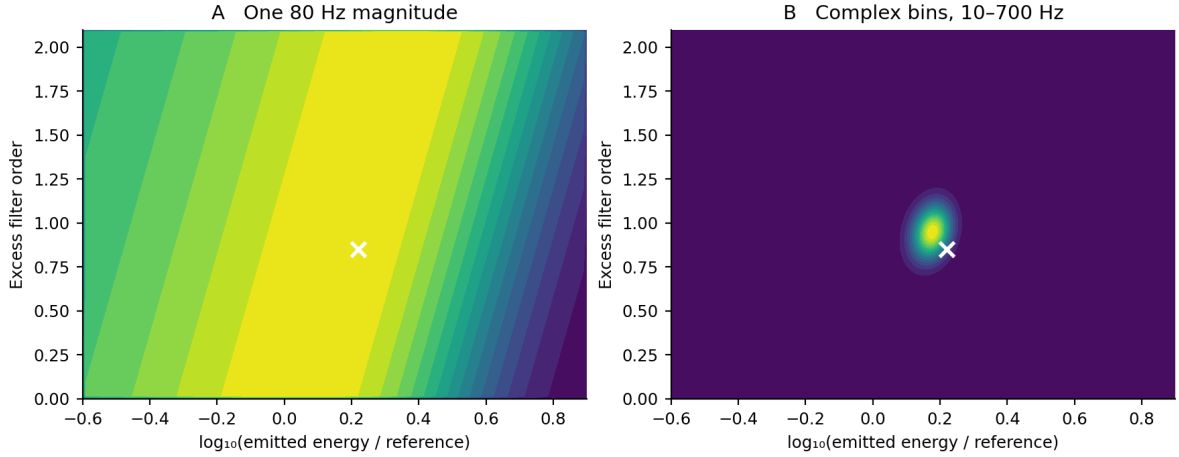

Figure 9: Relative grid-mass contours for one magnitude and a band of complex coefficients. The white cross identifies the parameters used to synthesize the data. Colors are rescaled within each panel.

e was 0.1745, with equal-tail 95% interval [0.0927, 0.2493]. The median a was 0.9490, with interval [0.7398, 1.1604]. Halving the grid resolution changed these medians by approximately 0.00013 and 0.000022. The single-bin magnitude analysis gave intervals [−0.5592, 0.7648] and [0.0573, 2.0508], reflecting the broad confounding retained by the observation scheme. Correct coverage over a population of natural falls was not assessed. In particular the two-parameter posterior cannot diagnose misspecification of mechanisms held fixed in both generator and estimator.

What if the goal is the entire source pressure coefficient rather than its energy? A separate reconstruction test holds the transfer function including extra loss known, then corrupts 160 realizations with independent Gaussian noise. Recovered source waveforms are evaluated over the full one-second window by normalized squared error, $\|\hat{s} - s\|^2 / \|s\|^2$. Direct division by the channel amplifies noise catastrophically in strongly attenuated bins, giving median normalized error 4.52×10^6. Even a transfer function with no exact zero can be effectively uninvertible at finite precision or noise. A linear spectral regularizer, using a design spectral envelope computed from a pulse 20% shorter than the true one, reduced median error to 0.365. The program also fit the amplitudes of the two correct time-domain basis pulses with least squares after propagating them through the known channel. This restricted fit gave median error 0.0271 and a 10th-to-90th percentile interval [0.00183, 0.11768]. The improvement reflects strong, correct prior knowledge about shape and timing. It would be inappropriate to conclude that ground evidence or an arbitrary acoustic record reconstructs a historical tree collapse to three percent error.

The experiments expose a useful asymmetry in the original question. At the producing end, a mechanical account and a justified radiation model suffice to predict an outgoing disturbance; neither requires data from the receiver. From the receiving end, even highly precise data can leave distinct combinations of source and path compatible with the same record. In a real investigation the missing empirical quantities include not only efficiency and wave shape, but how well the receiving instrument identifies causal origin

amid alternative sources. These limitations constrain the strength of an inference about a particular unwitnessed tree. They supply no feedback mechanism by which an absent hearer could cancel energy already radiated.

12. A prospective, unattended validation campaign

Claims, populations and registration

This is a proposed experiment. No field sites have been enrolled and no results from the campaign are asserted. Its primary endpoint is whether an unattended airborne receiver can discriminate a bounded mechanical impact analogue from a matched sham. A second, observational arm estimates detection and localization for independently confirmed natural collapses. A third asks how much can be recovered after all acoustic and seismic records are withheld. Each arm answers a different identification question. The first allows a randomized comparison. The second measures performance on the target phenomenon but cannot randomize the weather, the source or the time of collapse. The third asks about preserved consequences and cannot, by itself, prove a particular pressure waveform.

Before collecting confirmatory data, deposit the protocol, analysis code, instrument specifications, coordinate system, episode criteria, randomization script and cryptographic digest of the sealed allocation list in a dated registry. Record land-manager authorization, access restrictions and a privacy contact for each site. The responsible field investigator and independent custodian sign the version. Perform an engineering pilot with six analogue pairs and at least two recorder-days per site for clock and noise characterization. Pilot records remain identifiable in the archive and are excluded from the confirmatory population. Any alteration to analysis after the freeze becomes a dated amendment. Publish pilot-informed changes with enough detail to reproduce both versions. If the budget supports fewer sites or fewer independent units than specified, register that change before collecting confirmatory events and revise the population to which inference refers.

The target natural population comprises whole-standing-stem toppling or stem breakage leading to major crown descent inside a surveyed plot during an instrumented interval. Guided lowering, isolated branchfall, slow lean without a distinct descent, and a tree already lying down are separate classes. A broken trunk can leave its stump standing and still meet the definition. To prevent ambiguous labels, define major descent operationally as displacement of the main crown attachment point by at least half its pre-event height, or a change in principal stem orientation of at least 45 degrees with persistent contact or entanglement at the new inclination. These are registration choices that support reproducible annotation, rather than a universal definition of treefall. If either criterion is obscured, label the episode indeterminate. Record species where identified, stem diameter, estimated height, mode of failure, crown condition, contact substrate, terrain slope, and whether secondary branchfalls or other stems moved. One storm may produce a cluster of events. Preserve the cluster identifier.

Deployment and calibration

First inventory rights-cleared public archives and retain their provenance, channel metadata and label confidence. They can supply examples and held-out challenge material; missing calibration precludes an absolute sound pressure or efficiency estimate. The

natural arm uses 12 permitted plots chosen to span variation in canopy architecture, soil and weather. Register their boundaries and admissible analytical footprint before deployment; where feasible collect observations in more than one geographical region. Record forest age/structure, climate, understory, slope and winter snow as distinct descriptors. Old growth and boreal status can coexist. Any comparison between biome labels is exploratory. Observe at most 180 calendar days per plot within a two-year recruitment window. Include silent intervals and outages in the exposure log. Do not extend or shorten observation because an intermediate effect looks favorable.

For each plot install eight time-synchronized omnidirectional microphones around an approximately 80 m by 80 m footprint. Use four corner stations and four near side midpoints, adjusting to permitted paths and recording surveyed three-dimensional coordinates. Set six capsules at 1.5 m, one at 0.4 m and one at 3 m where installation allows. The height variation helps diagnose ground interference. Repeat position surveys after major weather events. Fit compliant windscreens with measured insertion responses. Record linear PCM at 48 kHz, 24-bit nominal resolution, fixed gain, anti-alias filtering, and disabled automatic gain control, compression and noise gating. Characterize the useful low-frequency response and the clipping pressure of the entire chain separately from the converter bit depth. Employ a low-gain duplicate channel at one near-source analogue station. Add at least three surveyed, triaxial ground-velocity channels with calibrated band coverage over 5–100 Hz, sampled at 500 samples/s or higher. Record triaxial acceleration on two neighboring stems with reversible noninjurious attachments and measured orientation; a mounting resonance is an instrument property. Where a permitted pre-existing fiber is accessible, archive its gauge length, coupling, orientation and interrogator settings as an exploratory strain-rate channel. Fiber, stem acceleration and ground motion have different transfer functions. Agreement across them requires an explicit band and timing criterion.

Use two fixed, silent video views where permitted, with known fields of view, clock marks, independent power and storage. Use infrared imaging only under applicable site conditions. Protect the sites of sensitive species, and restrict or mask imagery and incidental speech before public release. Record air temperature and humidity at two heights and atmospheric pressure, rainfall and a wind vector; log at least at one-minute intervals, with 10 Hz wind where a sonic anemometer is available. Register the measured heights. Add soil moisture and temperature, litter depth, snow condition when applicable and surveyed terrain. These observations constrain the duration and type of weather covariates. They do not determine the unmeasured three-dimensional wind field.

Before and after deployment, apply a traceably calibrated IEC 60942 class 1 acoustic calibrator at its certified frequency and level using the correct coupler and ambient correction [F8]. Document reference date and expanded uncertainty. Independently compare the frequency response of every assembled microphone, shield and recorder with a calibrated reference at multiple frequencies. A single calibration tone checks sensitivity at that tone. It cannot certify flatness, phase or an entire field recording chain against a sound level meter standard. Mark pressure level estimates with exceeding 1 dB pre/post sensitivity disagreement as quality failures pending time-resolved correction. Retain those channels for a separate timing-only analysis if clock evidence supports it. Verify geophone

and accelerometer gain, polarity and cross-axis alignment against a reference excitation before and after deployment. Check self-noise on quiet bench records and cross-channel electrical pickup on terminated bench inputs.

Distribute GNSS-disciplined pulse-per-second marks to recorder timing channels, or a common hardware clock where canopy reception fails. Electronic clock marks should enter through isolated timing channels that cannot feed the air-pressure input. Estimate an affine offset and drift between successive marks for each channel, and inspect residuals for dropped samples, steps and holdover. Perform surveyed, low-level acoustic sweeps at setup and retrieval and after maintenance. Use a source reference near the speaker and characterize the speaker's frequency-dependent directivity and finite aperture; record its orientation. In a noncompact near field the reference is only a source monitor. Repeat at two or more heights and several azimuths. Limit playback to the authorized level, duration and ecological season. A location-grade record requires residual clock uncertainty below 0.2 ms and station coordinate uncertainty below 0.10 m. At 343 m/s the clock limit corresponds to 0.069 m of one-way travel. Tracking errors in effective sound speed and uncertain source geometry generally add further uncertainty. A channel failing the timing limit may still yield a calibrated single-channel exposure. Network synchronization and canopy-related constraints have precedent in terrestrial acoustic arrays [F9].

Controlled comparison and locked primary analysis

Use naturally shed wood or wood from already scheduled maintenance in a guarded laboratory impact apparatus operated under the site's normal authorization. Use a fixed test height, sample its center-of-mass descent, and photograph the substrate and position. Define the allowable mass and drop-height range in the registration after pilot safety qualification. Use one distinct specimen in each of 30 independent confirmatory sessions. For each pair randomly assign the order of a wood-on-substrate impact and a sham actuator cycle without the impact. Install an acoustically isolated trigger or equivalent system, then verify the sham independently; the release itself can radiate. Keep personnel away from the recording room during both intervals. Use common arm geometry, gain, pretrial background and trigger bookkeeping; schedule the second trial only after the first impulse response has decayed and the room has been reset. If the apparatus itself changes between conditions, the estimand is discrimination of the whole intervention. A secondary control compares actuator-only, isolated contact-only and complete-cycle records to locate that difference.

Fix one primary reference receiver 4 m horizontally from the nominal contact point at 1.5 m height. All primary files have the same duration and a common nominal trigger zero for both conditions. On stable portions of each file convert counts to pascals, subtract DC, and apply a registered fourth-order 125–4,000 Hz Butterworth band-pass implemented as second-order sections offline, with zero-phase filtering of a padded record. Retain the padding and package version; trim filter edges before scoring. Define the score as the difference between the mean square filtered pressure during zero to two seconds and the mean square during minus four to minus two seconds, in Pa^2. Both intervals have equal duration. The forced-choice rule selects the larger score in each pair. Resolve exact ties

by a committed independent fair-bit list. The analysis custodian receives randomized clip identifiers, trigger times and calibration corrections, with the condition labels encrypted until all scores are fixed. Chance success under the sharp no-effect null with independent within-pair random allocation is one half. With 30 pairs, at least 20 correct yields an exact one-sided tail of 0.04937. Under independent equal success probabilities of 0.75 and 0.80 the corresponding prospective powers are 0.8943 and 0.9744. These are design calculations, not estimated performance. If session effects make success probabilities heterogeneous, the binomial power calculation is only a planning model. The randomized null remains conditional on the allocation design and no carryover.

Include clipped or unusually quiet pairs in the occurrence ledger. Predeclare an instrumentation failure only from nonacoustic evidence such as recorder diagnostics showing no saved sample file, failed calibration or dropped time coverage. For the primary all-scheduled sensitivity analysis, treat unscorable pairs first as incorrect and then as correct, displaying the resulting bounds. The exact complete-data randomization test uses only a complete prespecified sample, or missingness demonstrably independent of assignment under the sharp null and the reported conditional sample size; otherwise mark the primary inference indeterminate. Never replace difficult events after decoding the labels. Source excitation may span more than the chosen bands. Failure of this test therefore concerns the chosen apparatus, detector and trial conditions. The protocol licenses neither a universal absence claim nor an acoustic efficiency from one microphone.

Natural arrivals, independent evidence and unattended reconstruction

A separate truth team works from silent video, mapped stem state, repeat imagery and ground inspections conducted when the site manager permits safe access. Archive before/after images as interval-censored even when they contain a convincing new gap. A monthly or weekly image can independently substantiate canopy disturbance while supplying little timing information [F7]. Grade A requires a visible qualifying event in synchronized imagery with time accuracy within one second and source position within 3 m by survey or stereo geometry. Grade B requires physical confirmation of a new qualifying fall with a possibly broad time interval. Grade C is an unconfirmed candidate. Two independent labelers classify records without access to acoustics, ground-motion alerts, or each other’s labels. A third resolves conflicts and archives all initial assessments. Apply the truth search uniformly over the predefined camera footprint and observation period. If video is gathered only after a microphone trigger, misses cannot contribute to the denominator and true sensitivity is unidentified.

The acoustic analysts receive a copy of continuous data stripped of the truth channels. A frozen exploratory detector scores two-second windows advanced at a one-second stride. At each station use the same band as the analogue primary and a baseline median over valid preceding windows spanning ten minutes. Compute the ratio of current mean square to baseline median using an instrument-specific positive floor derived from measured bench self-noise. Define the array score as the third largest available station ratio; fewer than three valid stations are recorded as downtime. On separate pilot negatives choose a single threshold at the 99.9th percentile of valid array scores using a

stated quantile convention; lock it before confirmatory monitoring. The threshold selects a nominal pilot operating point and does not guarantee an equivalent field false-alarm rate. Merge exceedances with start times less than five seconds apart into one episode, retaining its earliest trigger and peak score. Require at least four synchronized arrivals for an exploratory constrained source-location fit, minimizing arrival residuals against surveyed coordinates and a meteorology-adjusted direct-path model. At the recovered point form the arrival Jacobian for coordinates and onset, scaling the onset column by using the range-equivalent parameter ct_0. Report a location only if its largest-to-smallest singular-value ratio is below 100, the fit is unique within the footprint at the calibrated error scale, and the 95% horizontal confidence region has maximum diameter below 20 m. These thresholds are design choices to validate in the pilot. Four arrivals alone give no residual degrees of freedom for a four-parameter fit. With only four arrivals report the fit as exploratory and validate against camera position; use a near-ground fit only when independent evidence supports a ground contact. Keep unstable or outside-footprint episodes in the detection analysis.

Match alerts one to one to Grade A truth within a preregistered temporal tolerance from one second before first visible descent through four seconds after final visible contact. A long event can generate separated alerts; only the first unique match counts toward sensitivity, and later ones are reported as duplicates. For overlapping truth episodes assign matches by smallest absolute deviation from first visible major contact, then by fixed ID. Where contact is not visible, use the midpoint of the truth interval and flag the case. Report sensitivity over all Grade A events in synchronized, instrumented coverage; also display broader bounds including excluded outages. Report alerts per station-network day of valid negative exposure, a precision estimate over adjudicable alerts, and uncertainty from a bootstrap over plot and contiguous storm blocks. If there are too few independent blocks for stable intervals, give the event table and describe the limitation. Grade B contributes to interval-censored analyses but cannot be counted as a timestamp-confirmed waveform. Include errors from synchronized equipment, non-tree transients, nearby rockfall, branchfall, and overlapping weather. Use a separate sample of at least 300 preregistered nonoverlapping two-second negative windows from distinct site-time blocks where feasible to estimate window-level false-alarm probability. Even zero errors among 300 independent representative negatives gives a one-sided 95% upper bound near 0.00994. Correlated windows will support a weaker inference.

A third team receives only before/after ground photographs, visible root-plate displacement, branch debris, soil disturbance and the bounded plot histories. Include independently verified no-change plots as foils, randomized within strata, and withhold the acoustic and timing dossiers. Ask for probability of a qualifying fall, a 90% location region, mode-of-failure category and a time interval. Score occurrence using the Brier score, location by containment and area, and time by containment and interval width. The ground-truth labels and the third team's reconstruction cannot rely on exactly the same residual photographs on the confirmatory scoring set; reserve Grade A video as reference. Compare inference before and after adding residual traces in a blinded crossover on disjoint, counterbalanced cases. Improvement shows that traces retain information about the specified target variable. Reconstruction of a break or orientation need not establish the air-pressure time series. A comparison with inferred sound level is admissible

only at calibrated held-out microphones, with error bands and recorded geometry.

Estimation, uncertainty and observer intervention

For a received transient report the pressure-squared exposure $\int p'^2 dt$ in Pa² s over a stated event and frequency window. Estimate the background contribution from matched off-event control intervals under the same meteorological state. A background-subtracted point estimate can be negative because of sampling uncertainty and cross terms. Retain that signed value for unbiased comparisons under the independence model; define detection and positive energy interval estimates separately. Estimate true radiated energy only in controlled trials equipped with co-located pressure–particle-velocity probes or phase-matched intensity probe pairs and adequate solid-angle quadrature. Correct probe phase mismatch, compare independent surface radii and account for the ground boundary. Report the angular and spectral coverage, unmeasured flux and reflected contributions. An array of pressure sensors on a flat woodland perimeter measures neither the entire enclosing surface nor all active velocity components. Its data cannot establish an absolute tree acoustic efficiency without a validated radiation model and a separately measured mechanical energy denominator.

For analogue efficiency, weigh each specimen on a calibrated scale; survey actual center-of-mass height change and estimate translational and rotational velocities from calibrated high-speed optical tracking immediately before and after contact. Use a replaceable substrate with initial condition recorded, measure support loads and displacements, and report strain storage, rebound and fragment velocities where observable. Define gravity-to-air efficiency against measured gravitational work, contact-incident efficiency against pre-contact kinetic energy, and stage-loss efficiency against the net mechanical debit across the contact interval after accounting for other work and retained energy. Thermal and unobserved deformations remain explicit uncertainties. Measured time-integrated support force is ground impulse and cannot be substituted for aerodynamic impulse in the dipole bound.

The uncertainty ledger must record calibration sensitivity and drift in dB, instrument response and phase, timestamp uncertainty, position and source-extent uncertainty, wind and effective speed, clipping, windscreen state, baseline nonstationarity, camera coverage and label disagreement. Clock and coordinate calibration can be propagated through arrival-time likelihoods; in a direct-path approximation $t = r/c$, so the first-order dependence is $dt = dr/c - r\,dc/c^2$. Propagate shared temperature, reference calibrator and common clock uncertainties jointly across receivers. Distinguish uncertainty conditional on a fixed atmospheric model from error found by held-out known-source tests. Report detection intervals separately for the closed analogue population, camera-observable natural events and interval-only disturbances. Neither the number of microphones nor the number of samples per event increases the independent biological event count.

An unattended recorder couples to the wave to transduce it. A support, windscreen or nearby person can scatter the field. Test practical back-action in a calibrated analogue by randomizing a dummy instrument body into or out of the relevant location while measuring at an independent fixed receiver. Compare paired differences against a prespecified

±1 dB band by an interval-based equivalence analysis with the number of pairs and precision registered from pilot variance. Even successful equivalence establishes a bound for the chosen observable and geometry; it cannot establish exact field invariance. The causal counterfactual “no people within this plot during the event” can be operationalized using site access logs and restricted visits, within stated coverage. Conscious experience of every potential organism cannot be audited by this apparatus. Passive monitoring networks in tropical forest are documented engineering precedents [F10]. Their existence supports feasibility of unattended acquisition, without supplying this experiment’s outcomes.

Acquisition capacity can be budgeted before recruitment. At 48,000 samples/s and three bytes per sample, eight mono microphones produce about 99.5 GB per plot-day before headers; 12 plots recorded for 180 days would produce approximately 215 TB of uncompressed acoustic samples (decimal units). Video, environmental data, duplicate channels, checksums, redundant copies and transfer staging add to that figure. Register the measured power draw and channel uptime under site conditions, encrypted media rotation interval, spare capacity, and the destination of each copy before installing a station. Continuous coverage is essential for enumerating false alarms and cases missed by the candidate detector. If capacity forces duty cycling, publish the sampling probabilities and reformulate the inference over prospectively covered intervals.

The release package should include clock marks, calibration certificates, raw samples where privacy permits, maps of the admissible footprint, meteorological series, firmware and filter versions, label adjudications, randomization commitments, analysis scripts and a hash manifest. Withhold identifying voices and precise locations of protected wildlife in public derivatives while keeping an authorized restricted audit copy. Report unobserved intervals, all amendments, data loss and deviations beside the main estimate. A well-documented nondetection with limited bandwidth and coverage remains an experimental result even when the question of all emissions outside that coverage remains open.

Mathematical appendix on certifying what the tree emitted

Definition of the estimand

For an outgoing linear disturbance in homogeneous, stationary, lossless air, write the real far-field pressure as $p(rn, t) = F(n, t - r/c)/r + O(r^{-2})$. Here n is a unit vector and the reference state has impedance $Z = \rho c$. Assume a localized source, finite integrated energy, no incoming radiation, and sufficiently regular remainders for the far-field flux limit. Define $d\mu = d\Omega/(4\pi)$. The emitted energy is

$$E = \frac{4\pi}{Z} \int_{\mathbb{R}} \int_{S^2} |F(n, s)|^2 \, d\mu(n) \, ds.$$

Indeed the leading radial velocity is p/Z, and the factor r^{-2} in energy density cancels the area factor r^2. The units of F are Pa m, making the expression an energy in joules. This construction labels the output of a source, including when no receivers exist. A real forest may absorb an outward wave before it reaches infinity. There the investigator must move the accounting surface to a specified finite distance and use actual active flux or a validated outward-wave decomposition. A vanishing flux at infinity in a lossy medium says little about a physically audible release a meter from the trunk. At a reflecting boundary even net active flux can vanish in the presence of sound.

Suppose that a time-aligned array replaces the ideal surface integral. Let V be an angular subspace of dimension d, with real basis functions orthonormal in $L^2(S^2, \mu)$. Assume $F(n, s) = \sum_{j=1}^{d} a_j(s)\phi_j(n)$. A synchronized sensor at direction n_i at radius r_i measures a pressure record which, after background removal, multiplication by r_i and subtraction of the propagation delay, estimates $F(n_i, s)$. Write $A_{ij} = \sqrt{w_i}\phi_j(n_i)$ and let $y = Aa + e$, where y is the vector of square-root-weighted records. The weights sum to one. In a non-homogeneous forest a transfer operator, including its calibration errors, would replace this matrix; the following experiment concerns free-space propagation.

Proposition 1. A conditional interval for emitted energy

Let the time-domain vector error have norm at most ϵ in $L^2(ds; \mathbb{R}^N)$. Let σ_+ and σ_- be the largest and smallest singular values of A, where the minimum is taken over all unit vectors in the **domain**, so a nontrivial kernel gives zero. If $0 < \sigma_- \le \sigma_+$ then

$$\frac{4\pi}{Z} \frac{(\|y\| - \epsilon)_+^2}{\sigma_+^2} \le E \le \frac{4\pi}{Z} \frac{(\|y\| + \epsilon)^2}{\sigma_-^2}.$$

Proof. At each time $\sigma_- \|a(s)\| \le \|Aa(s)\| \le \sigma_+ \|a(s)\|$. Squaring and integrating gives the same norm bounds on the complete histories. The triangle and reverse triangle inequalities enclose $\|Aa\|$ between $(\|y\| - \epsilon)_+$ and $\|y\| + \epsilon$. Orthonormality makes $E = (4\pi/Z)\|a\|^2$. Substituting establishes both bounds. A receiver network can lower-bound energy from a sufficiently strong record even if it has a nontrivial kernel, provided the upper operator

bound still holds. In a finite-dimensional band-limited model point evaluation is bounded. Point evaluation on the unrestricted space of all square-integrable angular patterns need not be bounded. Dropping the modal assumption can therefore affect *both* sides of the inference.

Sharpness and natural units. Take a coefficient vector history parallel to an extremal right singular vector times a normalized waveform, and align the permitted error with the corresponding data. One of the two inequalities can then be saturated. Different estimates from a particular data vector are possible using its orientation. The interval is a worst-case guarantee from the data norm alone. When a noise model is Gaussian, the error norm has no deterministic finite upper bound; a probability statement requires a separately justified quantile, a finite-dimensional observation window, and a noise covariance. The theorem cannot turn an unspecified noise floor in dB into a guaranteed number of joules.

An exact control with twelve microphones

Choose the twelve unit vectors obtained by normalizing the cyclic permutations of $(0, \pm 1, \pm\varphi)$, where $\varphi = (1 + \sqrt{5})/2$ and the two signs vary independently. Use equal weights. They are the vertices of the regular icosahedron. The classical spherical design integrates polynomials up to degree five exactly [R4]. For angular amplitudes of degree at most two, every instantaneous squared amplitude has degree at most four. The discrete average of the squared pressure, after range and time alignment, therefore equals the spherical average. Since this holds for every time, integration gives total energy exactly. This equality is about an angular model and sensor geometry. It makes no claim that real trees only excite the first nine modes.

One can check this without assuming a quadrature theorem. An orthonormal basis for degrees zero through two on the normalized sphere is 1, the three coordinates multiplied by $\sqrt{3}$, the three distinct mixed products xy, yz, zx multiplied by $\sqrt{15}$, and the functions $\sqrt{15}(x^2 - y^2)/2$ and $\sqrt{5}(3z^2 - 1)/2$. Pairwise integration or substitution checks orthogonality. The archived program forms its 12×9 evaluation matrix, divides by $\sqrt{12}$ and multiplies the transpose back. The maximum entrywise difference from the identity is 8.89×10^{-16} or less in the recorded run. Repeating the calculation on an independent Gauss–Legendre by periodic-azimuth grid gives a maximum error below 2.8×10^{-14}. Twelve equally spaced microphones on the equator instead give rank five. Adding receivers in the same plane did not measure all nine degrees of freedom.

Proposition 2. One omitted radiation mode defeats the certificate

Set $h(n) = \sqrt{105}\, xyz$. For each icosahedral direction at least one coordinate vanishes, so every sample of h vanishes. Its spherical mean square equals one. To check the normalization, uniform directions have z uniform on $[-1, 1]$ and conditional azimuth uniform on the circle. Consequently $\langle x^2 y^2 z^2 \rangle = (1/8)\langle z^2 (1 - z^2)^2 \rangle = (1/8)(1/3 - 2/5 + 1/7) = 1/105$. By sign symmetry, h is orthogonal to every polynomial of degree at most two. It is a degree-three spherical harmonic since $\Delta(xyz) = 0$.

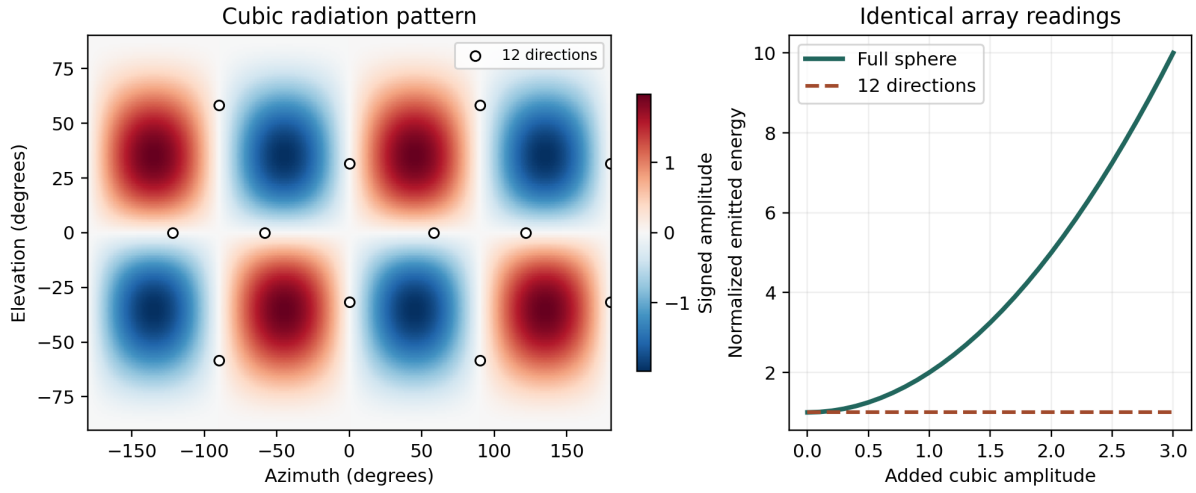

Figure 10: Twelve receivers lie on the nodal set of the cubic pattern. The dense sphere integral measures the additional energy while the array estimate stays fixed. Simulated normalized amplitudes and energies.

Let u be any unit-norm combination of the nine lower modes, and let q be any nonzero finite-energy pulse. The fields with far-field amplitudes $u(n)q(s)$ and $(u(n) + kh(n))q(s)$ have identical time histories at all twelve microphones for *every* real k. Their emitted energies are in the ratio $1 : (1 + k^2)$. Setting $k = 3$ gives a tenfold difference. Pure $h(n)q(s)$ also supplies an example of positive radiation and zero readout at every sensor. A common band-limited, real pulse supported away from zero frequency in Fourier space can be used to avoid a static component. Outgoing multipoles on an enclosing sphere furnish admissible linear exterior solutions at each positive frequency, with appropriate boundary drive. This is a radiation-pattern construction. No inference is made that a particular wild tree realizes the designed pattern.

The numerical trial draws a single reproducible unit vector of lower-mode coefficients and varies k over 31 points. It obtains 9.99999999999997 and 1.0 for the final sphere and array energies in normalized units. Rescaling the pulse amplitude, duration or impedance changes the common scale. A tenfold *ratio* is the result. Neither the simulation nor the analytical example assigns joules to a tree. The eight-decimal and machine-precision figures in the archive report arithmetic agreement, not experimental precision.

What the example identifies

A zero at a single microphone can arise from its placement on a radiation node. An entire finite array can have the same defect. Conversely, a finite array can give an exact energy integral over a class considerably richer than an isotropic point source. An observer clause must therefore specify both what was observed and which source patterns have already been excluded on independently justified grounds. Even if every reading lasts forever and is acquired without electronic noise, those conditions alone do not create angular coverage.

Suppose evidence elsewhere places an upper bound b on the time-integrated norm of modal coefficients outside the modeled subspace, and a separately validated upper bound L maps those coefficients to the weighted sensor norm. Treat the term Lb as extra observation error in Proposition 1. Orthogonality gives total squared norm equal to modeled squared norm plus the squared tail norm. The resulting total upper bound adds $(4\pi/Z)b^2$ to the modeled upper bound. A bound only on a nominal angular cutoff or a belief that high multipoles are “small” does not provide either b or L. An angular smoothness class with an appropriate bounded sampling theorem could supply additional information. A calibrated set of observed patterns might support a statistical interval with defined coverage. The distinction between these two forms of assurance should be specified before a recorder is deployed.

Different prior assumptions also govern a positive detection. If tree-generated pressure is the only allowed explanation of a high-quality signature, a positive, above-error sample in the model certifies a positive event contribution. If plates on a nearby bridge, rainfall impacts, or wind on a microphone port can generate the same observation, source attribution is a separate inverse problem. A nonzero channel output certifies activity of that channel; causal attribution requires either a contrast, independent labels, or a sufficiently restrictive source model. These are two distinct gaps between a field trace and an answer about what *this tree* made.

Can a finite pressure array miss a whole transient?

Suppose an ideal homogeneous unbounded fluid surrounds an impermeable sphere of radius a. Its boundary undergoes small normal vibrations. The initial medium is at rest and there are no incident waves. Place N stationary point-pressure receivers at arbitrary locations outside the sphere. Could they rule out a radiating boundary motion by registering exactly zero pressure perturbation for all time?

Proposition. There exists a nonzero causal surface excitation for which every such receiver reports zero pressure throughout the experiment while the source radiates positive energy. This applies to any finite N under the stated model. The excitation depends on the chosen array.

Proof. Choose l with $2l + 1 > N$. Real spherical harmonics of degree l span a vector space of dimension $2l+1$. Evaluating a member Y of that space at the receivers' angular positions gives a linear map into $\mathbb{R}^N$. Rank-nullity gives a nonzero Y vanishing at every receiver direction. Normalize its spherical squared integral to one. Choose a nonzero smooth causal pulse $v(t)$ of finite duration and zero integral. Prescribe normal boundary velocity $v(t)Y$. The time integral condition permits return to the same surface configuration. An arbitrarily small velocity multiplier preserves the linearization for a fixed pulse.

For the time convention $e^{-i\omega t}$, the outgoing pressure at positive angular frequency is

$$p_\omega(r, \hat{x}) = \frac{i\rho c\, \hat{v}(\omega)}{h_l^{(1)\prime}(ka)} h_l^{(1)}(kr) Y(\hat{x}), \qquad k = \omega/c.$$

Separation of variables in the homogeneous exterior Helmholtz equation gives the outgoing spherical Hankel function. The derivative is with respect to its dimensionless argument. Multiplying the radial derivative by $1/(i\rho\omega)$ recovers the boundary velocity. The derivative in the denominator cannot vanish at real positive argument since the real spherical Bessel functions of first and second kind have a nonzero Wronskian [A4]. Every receiver sees zero pressure at every frequency, even when receiver ranges differ. Reality gives the negative-frequency result by conjugacy. For directions where Y differs from zero the field has a nonzero outgoing coefficient on a set of positive frequencies of positive measure. Hence its integrated outgoing energy is positive. The shared radial response within a single degree preserves every angular null over the whole pulse.

Quantitative scale. For a sinusoidal peak velocity V the outward mean power and its ratio to the patchwise plane-wave reference are

$$P_l = \frac{\rho c |V|^2}{2k^2 |h_l^{(1)\prime}(ka)|^2}, \qquad \sigma_l = \frac{P_l}{\rho c a^2 |V|^2/2} = \frac{1}{(ka)^2 |h_l^{(1)\prime}(ka)|^2}.$$

These expressions follow by integrating the harmonic far-field intensity over a sphere. For $x = ka \ll 1$ at fixed l, the leading term is $\sigma_l \sim x^{2l+2}/[(l+1)^2((2l-1)!!)^2]$, where $(-1)!! = 1$ [A4]. For degree zero, $\sigma_0 = x^2/(1+x^2)$ exactly. Angular nulls and small total

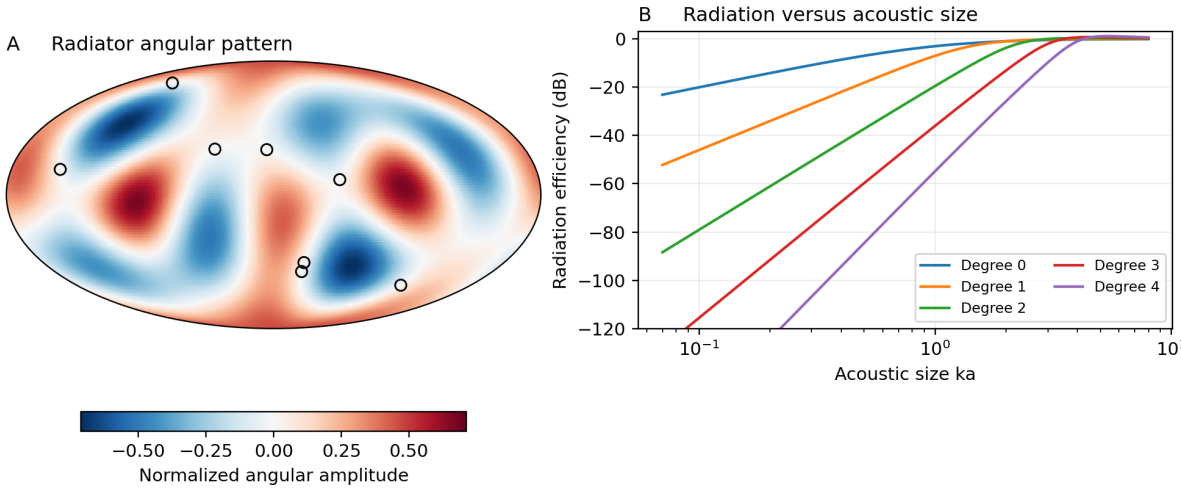

Figure 11: A degree-four source is blind at eight receiver directions; radiation efficiencies show the effect of angular order. Circles mark point receivers.

radiation are distinct mechanisms. Adding a receiver in a bright direction remedies the first. An arbitrarily quiet source still requires sufficient sensitivity.

Numerical experiment. Eight independently sampled directions give an eight-by-nine evaluation matrix at degree four. With seed 54308 the matrix has rank eight. Taking a unit right null vector gives a maximum absolute angular value below 3×10^{-16} at the microphones. A 241-by-121 angular grid attains 0.7113. A 0.1-degree displacement of each receiver along a randomly chosen fixed tangent raises the largest receiver value to 0.00345. A one-degree displacement raises it to 0.03425. At $ka = 1$ the computed efficiencies for degrees zero through four are 0.5000, 0.2000, 0.01124, 0.0002522 and 0.000003332. The source code tests the monopole result against its closed form at 240 acoustic sizes. Directions, singular values, coefficients, projected amplitudes and efficiencies are retained.

Scope. A velocity probe can respond to an angular derivative at a pressure node. An acoustic reflector or an extended microphone can change the null. A tree cannot generally prescribe arbitrary normal velocities on a spherical boundary. This construction supplies a counterexample to a proposed inference from complete finite-array silence to absence of emitted sound. It supplies no frequency of occurrence in nature. The result applies established separation of variables and linear algebra to an explicit observational question. No priority claim is made.

Glossary and formal ontology

A collapse is an extended event with a material source, onset interval and causal descendants. The following vocabulary defines the relations used in the verdict; a relation can have a physical instance even if the instance was never recorded.

Object or relation	Definition and verification criterion
Mechanical vibration	Time-varying displacement or strain around a reference state. It can be confined to the wood.
Acoustic generation	Source work that excites a propagating mechanical mode of a specified medium. Specify the source, initial state and background.
Airborne field	Pressure and particle-velocity perturbations in the air. Separate acoustic, hydrodynamic and quasi-static terms when interpreting a local transducer.
Elastic or seismic field	Stress and displacement propagating in a solid or through the ground. Its existence does not give an air pressure in pascals.
Radiation	Energy carried away from a reference source neighborhood in outgoing modes. Net flux through an arbitrary surface in a reverberating field needs directional interpretation.
Exposure	Integral of squared pressure over a selected interval, in Pa^2 s. A receiver quantity.
Active intensity	Time-averaged pressure–particle-velocity product. A vector in W per square meter.
Radiation impedance	Relation between driving pressure or force and boundary velocity under a specified geometry. Its resistive part supplies net power for harmonic forcing.
Transfer function	Frequency-domain map from a specified source input to a receiver output under approximately time-invariant conditions.
Biological detection	A stimulus-attributable change in a living receiver satisfying a defined physiological or behavioral criterion.
Artificial detection	A transducer and decision process deliver an event classification at a stated operating point. Continuous sensing alone need not classify.
Auditory transduction	Conversion of mechanically coupled stimulation into receptor and nerve activity in an auditory system.
Neural representation	Measurable response structure that covaries with features of stimulation under controlled conditions. It can occur without a subsequent report.

Object or relation	Definition and verification criterion
Auditory experience	An experienced auditory quality. An event-specific assertion requires a causal connection to this collapse.
Information encoding	Dependency between a defined latent variable and a physical channel variable in a specified ensemble.
Information accessibility	Ability of a specified measurement and inference operation to retain and extract that dependency.
Historical reconstructability	Achievable accuracy for a defined past quantity, loss function, evidence set and model class. Unique waveform recovery is stronger than event identification.
Observer independence	Existence of the physical event under a specified model without any conscious observer as a necessary causal input. Physical changes to boundary conditions still matter.

An auditable data record should carry a tree-event identifier, medium, source region, time origin, receiver channel and response window. A record of a record also needs the identifier of the earlier record; playback needs a new physical-source identifier. Two measurements can have the same event identifier while referring to different wavefields. Likewise, two copies of a file can be perfectly redundant evidence, despite the existence of two physical storage media.

Uncertainty and limitations register

Unresolved quantity	Consequence for inference	Evidence that would narrow it
Fraction of mechanical loss entering air	Gravity sets an energy scale, not a universal radiated yield	Synchronized independent mechanical denominator and enclosed calibrated flux, with uncertainty in missed aperture
Root, soil and crown dynamics	Endpoint geometry admits different impact spectra	High-rate motion and substrate records with documented material and contact states
Atmospheric and ground transfer	A single receiver confounds emission and propagation	Reference sources at multiple locations, wind and temperature profiles, surface impedance and held-out paths
Unobserved angular modes	Exact measurement at available microphones can leave total energy unidentified	Defensible modal cutoff or a quantified unresolved tail, plus adequate angular coverage
Receiver noise and event scanning	A per-window false alarm does not determine deployment-wide error	Event-stream evaluation including storms, ambiguous cases and real outages
Site selection and fall rarity	Triggered records can favor conspicuous events	Independent optical or mechanical ascertainment and documented monitored site-time
Natural-event ground truth	Short impulses may arise from other storm processes	Independent labels with uncertainty and candidate alternatives
Sensory or conscious state	Detection and report dissociate for some organisms and conditions	Species- and state-specific calibrated tests; no single marker settles all cases
Retrospective waveform recovery	A damaged trunk may establish fall occurrence while leaving many histories possible	Contemporaneous channels with known transfer and controlled timing
Ontology and historical priority	Definitions can be explicit even where authorial priority or metaphysics is undecidable	Earlier authenticated sources or a testable differentiating physical premise

The source review is interdisciplinary and targeted. Its coverage centers on primary case records, constitutive and propagation results, measurements in forests, physiological experiments, philosophical texts, information bounds and the history of the question. It is not a registered systematic database census. The labels in the annotated bibliography index claims and sometimes point to the same work from different disciplines. Counting those labels as independent replications would inflate the evidence.

Original contributions and prior art

Result in this investigation	Status and intellectual provenance
Conditional emission criterion for exposed motion	Application of established exterior uniqueness and the normal-velocity boundary condition. The distinction from compact volume forcing is essential.
Minimum radiated energy at fixed compact air-force impulse and duration	Variational derivation from the classical dipole radiation formula; equality case and dimensions given in the acoustic chapter. No priority claimed.
Emission interval from sampled angular records	Singular-value bounds plus energy flux supply a deterministic certificate conditional on a finite source model and bounded data error.
Twelve-sensor energy ambiguity	A worked application of spherical design theory. The synthetic example and reproducible cross-check are contributions of this investigation; spherical harmonics and quadrature are established mathematics.
Broadband null for any finite pressure array	Constructive specialization of spherical separation and rank–nullity with positive radiation. Assumes an ideal symmetric exterior and engineered source motion.
Bound on reconstructing historical waveforms	A two-history overlap inequality applied to residual evidence. The underlying minimax and testing methods are established.
Coupled synthetic experiment and field campaign	Reproducible conditional calculations and a prospective, independently labeled observational design. These do not supply new field measurements.
Historical verification	Comparison of inspected primary texts and an earlier newspaper attestation. The cited archival investigators receive discovery credit.

The contributions combine source physics and limits on observation. Their practical use is to state which assumptions would turn a field record into evidence about emission, and which assumptions can be tested separately. None supplies evidence for a new law of acoustics or a settled physical theory of consciousness.

Adversarial scientific review

Ten disciplinary perspectives were examined in five independently authored internal reviews. The following reports document the objections, checks, revisions, and residual uncertainties.

Independent internal technical review

This review was carried out in a separate computational workstream within the research environment. It is an independent recalculation and a cross-reading of other workstreams. It carries no representation of external human peer review or specialist accreditation. Its acceptance criterion is narrower than experimental validation. A defensible verdict must name the version of "make a sound" it tests, supply a sufficient physical premise, prevent a receiver failure from becoming a claim about the source, and disclose empirical quantities the available evidence cannot determine.

Mathematician's review

Strongest objection. Exterior uniqueness and nonradiating sources appear to establish opposite conclusions. A nonzero solution of a forced wave equation need not send any wave out of the support of its forcing. Conversely, in a connected, source-free homogeneous exterior of a fixed impermeable body, positive-frequency normal surface velocity cannot be nonzero while the entire outgoing field vanishes [A2, A3]. Conclusions must retain both the specified class of source and the region in which silence is asserted.

Independent check. Choose any smooth compactly supported causal pressure test field u inside an open spacetime set and define the forcing $f = (c^{-2}\partial_t^2 - \Delta)u$. Then u is the outgoing solution for that forcing with zero past data. It vanishes throughout the exterior. This counterexample suffices to disprove a universal implication from arbitrary forcing to a radiated wave. For the boundary source, zero time-averaged exterior radiation at one positive frequency implies a zero square norm of the far pattern. Exterior uniqueness implies pressure zero on the connected outside; the linearized momentum equation then forces normal velocity zero at the boundary. This second argument fails for an additional source in the exterior fluid, for an excluded cavity, for stationary deformation at zero frequency, or when zero intensity is asserted at a single angular point. A full unbounded sphere or an unbounded homogeneous exterior is an idealization. Neither result supplies a theorem about every large, fracturing, soil-coupled tree.

Aperture objection. An angular truncation can make a measured zero decisive only within its chosen subspace. The released 12-direction array integrates quadratic angular power from modes of degree zero through two. The integral involves degree at most four, within the exact quadrature. Independent code regenerated normalized spherical moments for every Cartesian monomial of total degree zero through five via gamma functions, without importing the quadrature program. Maximum discrepancy was below 4×10^{-16}. The cubic $\sqrt{105}xyz$ vanishes at all 12 directions, has unit spherical mean square and is orthogonal to the test family. The independent moment computation recovers the

sphere energy $1+k^2$ in the deposited mixing sweep to within 3.1×10^{-14}. These checks concern far-field coefficients. On a reflecting site a finite-radius sensor cannot automatically turn pressure squared into outgoing power. The single-degree appendix independently shows that a finite pressure array can even miss an entire pulse in an exactly symmetric medium.

Unresolved point. No lower bound on radiated joules follows solely from the event verb "falls." A positive lower bound requires classes of tree motion, ambient media and durational scales that exclude silent limits or actual quantitative constraints on the couplings. Finite measurement can falsify a particular predicted minimum. Finite measurement alone cannot establish exact zero energy over all unmeasured channels.

Statistician's review

Strongest objection. A physically motivated sensitivity sweep can look like a representative sample of real falls. If an uncertain log radiation yield is assigned a five-decade uniform distribution, it contributes to variability even in an otherwise highly constrained model. Changing that width, introducing correlations with branch geometry, or conditioning on an independently surveyed tree can change its importance. Numerical confidence within the chosen input distribution measures integration error or simulated randomness; it cannot turn an assumed distribution into evidence about a biome.

Detection and attribution. For additive Gaussian samples with common covariance and known template, subtracting the two log densities gives the normalized matched score, with mean shift d' under the alternative and unit variance. This permits verification independent of a decision routine [A5]. A per-window false alarm of 0.01 can lead to many daily alarms when onset is scanned. Continuous deployment requires a fixed search rule or calibration at the event-stream level. Even a perfectly timed positive transient yields weak evidence for a *tree* when storms also produce impacts from branches and other objects. Independent mechanical or visual event labels, hard negative examples, site-level separation and a detector fixed before test data reduce the problem. Residual risks include missing silent candidates in a sound-triggered selection procedure and reusing the same storm for multiple correlated labels.

Reconstructability. Two alternative pressure histories w_0, w_1 with separation Δ cannot both be accurately recovered from identical trace distributions. With equal priors and observations of outcome y, integrating half the overlap mass and applying $\|v-w_0\|^2 + \|v-w_1\|^2 \geq \Delta^2/2$ yields a lower bound $\Delta^2(1-\mathrm{TV})/4$. This was checked algebraically, including the cases of identical and disjoint observation laws. The bound needs a norm on possible waveforms and a distribution on accessible residuals; source energy alone supplies neither. Its use is an application of a standard two-point argument. The ordinary question does not come with a canonical source prior, receiver, loss function or frequency band.

Unresolved point. A conditional posterior for a single synthetic recording does not estimate real-world coverage, transportability between forest types, or natural fall incidence. Decision thresholds, quoted intervals and all biological interpretations require their own

validation population. A dead or missing sensor is a missing measurement. It is statistically different from both a good sensor recording background and a correctly attributed source generating no airborne radiation.

Computational reproducibility review

Strongest objection. Internal agreement can result from reusing the same suspect equation or unit convention. To test a different failure mode, the review independently integrated the rod dynamics by DOP853, checked dissipation by the loss of recoverable potential and kinetic energy, and derived the contact heat-plus-radiation allocation using the analytic energy ratio. With the declared nominal inputs the independent expected contact time measured from initial release is 3.8555051401 s, the impact angular speed is 1.2321617461 rad/s, and the subsequent compression–rebound interval is 0.01188583723 s. Of 79,025.7043 J gravitational potential released, 73,785.6168 J enters contact, and the specified contact rule assigns 38,957.9350 J to losses before dividing them between downstream channels. Multiplying by a prescribed 10^{-5} produces 0.38957935 J airborne radiation. The last number enters through a parameter assumption and does not corroborate that efficiency.

Dimensional checks. A projected rod strip with quadratic drag gives a torque proportional to $\rho D L^4 \dot{\theta}|\dot{\theta}|$, with units of joules. The time integral of torque times angular speed is energy. A radiating free-space pulse with reference coefficient $q(t)$ measured in Pa m gives $4\pi \int q^2 dt/(\rho c)$ in joules. Using a reference pressure at 1 m implicitly multiplies by $1\,\mathrm{m}^2$. Single-sided Fourier exposure of a real sampled pulse must count interior frequencies twice and the endpoints once. The conversion of exposure to d'^2 for independent temporal noise samples requires multiplying by sample rate as well as dividing by per-sample pressure variance. More samples at fixed bandwidth do not create independent information unless the noise model changes. Finite-dimensional white Gaussian samples are a declared synthetic model.

Evidence checks. The National Park Service Rainbow Loop catalog lists a tree-fall entry at the monitoring site [R1]. The Jasper Ridge report names an associated seismic signal and distinguishes the July 8, 1995 local date from July 9 UTC [R2]. The Quinault paper explicitly calls the strong seismic impulses *likely* treefalls, on the basis of seismologists' interpretation amid independently documented damage [R3]. None establishes calibrated airborne energy, exact source time and geometry for the numerical example, or the absence of all sentient receivers. The ASA terminology entry distinguishes propagated physical disturbances from sensations causally evoked by them [A1]. Tinnitus is evidence for an internal auditory phenomenon; it cannot establish that the external tree produced that phenomenon.

Open validation problem. The lack of calibrated joint measurements of input mechanical work and outward pressure–velocity flux for this actual source remains consequential even when all code checks pass. Shared model error survives exact numerical convergence. This is the principal separation between the numerical appendix and the proposed field campaign.

Executed acceptance tests and dispositions

The independent verifier in `support/independent_verification/recheck.py` executed **32 acceptance tests**, all of which passed with the saved inputs. Its machine-readable record states the measured difference and absolute tolerance for each comparison. The acceptance tests import no production-model code. Some tests compare published tables with an independent identity, while others compare independently solved models or estimators. Those categories have different evidential value.

Disputed result	Independent operation and observed outcome
Does the simulated rod have the stated impact energy and duration?	Integrated the angle–velocity system using adaptive DOP853 and located the horizontal crossing. The production fall time differed by 9.75×10^{-12} s, tip speed by 5.08×10^{-11} m/s and contact loss by 1.79×10^{-7} J or less. The latter used the closed-form energy ratio $1 - e^{-2\zeta\omega_n t_c}$.
Can the source spectrum be interpreted in joules?	Summed the released one-sided reference-bin exposures and used spherical flux. Agreement with an independently calculated allocated energy was within 2×10^{-12} J. This checks normalization of the stipulated acoustic share.
Are the path and threshold tables mutually consistent?	Reconstructed the east/west known-template separations from spectral-bin exposures, per-sample variance and sampling frequency. Matched the geometric delays and the theoretical operating curve. The theoretical detection probability at $d' = 2$ lies slightly outside the reported marginal 95% Wilson interval for that simulated row. Seven separate intervals need not all cover their targets. The remaining comparison should use the recorded counts and nominal uncertainty without retuning the run.
Does efficiency dominate merely because of its chosen prior?	Under the declared independent input intervals, the log-efficiency term contributes exactly $50^2/12$ square decibels to the variance. Dividing by total sample variance gives an analytic-ratio check of 0.811398 versus total-index estimate 0.811317. The close match verifies an attribution *under this prior*.

Disputed result	Independent operation and observed outcome
Does multiband Bayesian recovery use the right noise normalization?	Verified both posterior mass normalizations and the interior maximum. Reconstructed the seeded observation from the deposited clean record. Directly summing complex residual squares at two interior grid points gave a log odds difference of 0.5381747050410, agreeing with the deposited posterior ratio to within 1.2×10^{-13}. This tests a pair of likelihoods and the sample-domain variance convention. No coverage test across wild recordings follows.
Do the ancillary physical and experimental controls close?	Independently integrated the far-field mirror-source pattern in closed form at 256 and 1,024 Hz. The discrepancy from the highest-resolution deposited surface-flux values was below 5.3×10^{-15} W. Direct finite sums of binomial probabilities gave 0.04936857 under the fair-choice null and powers 0.89427188 and 0.97438374 at alternatives 0.75 and 0.80. The zero-among-300 one-sided 95% upper bound is 0.00993608 per independent opportunity.

Clean-copy reproduction. The reviewer copied the repository into a new temporary directory, saved the delivered checksum inventory separately, ran the two documented Python entry points with one OpenBLAS thread, and checked the outputs against the pre-run inventory. All 28 entries in that inventory matched. The comparison included numerical tables and figures. This was a separate execution under the same software environment; independent platform portability and empirical calibration remain open.

Mathematical disposition. Cross-reading of the conservation-law chapter confirmed the point-dipole constant $1/(12\pi\rho c^3)$ after angular integration, the T^{-3} sharp lower bound for specified *airborne* impulse, and its parabolic equality case. Direct substitution into the smooth cosine force test gives energy $\pi J^2/(6\rho c^3 T^3)$. The lower bound cannot accept a measured soil impulse in place of the force delivered to air. The certificate appendix correctly confines bounded point evaluation and singular-value statements to a declared angular class. The information chapter's residual-overlap bound has correct dimensions, limiting cases and direction of inequality. The conditions on injected force, observed modes, background comparison and residual observations are material parts of the conclusions.

Source disposition. Bibliographic spot checks covered the ASA, primary case records, scalar-wave nonradiation, the exterior Rellich theorem and Shannon's fidelity paper. The latter appeared in the *IRE International Convention Record*, volume 7, part 4. This review did not independently retrieve every entry in every subject bibliography. Field taxonomy and conscious experience remain matters of separate disciplinary evidence. Neither a matching archive digest nor a high-performing Gaussian detector can supply the missing universal theorem or prove what any particular animal consciously perceived.

Independent experimental acoustician and forest ecologist review

Review status. A separate model reviewer examined the mechanics, acoustic derivation and computational chapters, the repository parameter set, and the path-comparison table. This is a cross-author adversarial read, conducted from the perspectives below. The field chapter and protocol were authored by this reviewer; the mechanics contributor separately reviewed the protocol.

Experimental acoustician

Strongest objection. Assigning a nonzero efficiency to an effective damper makes a positive source an input of that experiment. The free-space pressure normalization plus an image ray can then shift the actual flux through the upper half-space. No three-dimensional tree radiation measurement in the study establishes the assigned efficiency. A pressure map alone cannot establish net active intensity.

Checks and disposition. The computation names its energy a *free-space equivalent*, labels the pressure-squared map a progressive-wave equivalent, and explicitly excludes source loading by the ground. The separately implemented rigid-half-space audit supplies velocity phasors, true vector flux and an enclosing-surface check. Four high-resolution hemisphere integrations gave a maximum relative error of 4.0×10^{-13} against the source-plus-image radiation-power identity. This confirms internal normalization for a prescribed monopole above a rigid boundary; the possible change in mechanical excitation by real soil remains open. The protocol now distinguishes measured airborne flux, pressure exposure and separate mechanical denominators.

Mechanics and physical sufficiency. A contact force transducer below the log measures momentum transfer to the substrate. Treating that impulse as the input to the acoustic dipole formula could manufacture a sharp lower bound on radiated energy. The source-physics chapter explicitly uses impulse applied to the air. Independently recalculating the smooth pulse examples from its analytic equation yielded 0.135159, 0.00865018 and 0.000135159 J for durations 0.02, 0.05 and 0.20 s. Agreement verifies the examples and exposes their sensitivity to unknown loading duration. The experimental section explicitly preserves the impulse distinction. Its enclosure method requires velocity and angular coverage. Finite-band instrumentation leaves unresolved energy above, below and between its sampled channels.

Weakest physical assumption. The exposed-boundary uniqueness argument is for a fixed smooth reference surface in a homogeneous unbounded fluid without another source. Root detachment, translation, canopy change, a nearby ground plane, and heterogeneous turbulent air violate that exact setup. The chapter limits its theorem accordingly. An uneventful microphone record cannot test unique continuation across all frequencies and directions. The issue remains open for the fully coupled natural event class.

Forest ecologist

Strongest objection. A homogeneous fictitious strip with an imposed loss is incapable of demonstrating that an actual stand attenuates by that amount. It has no individual stem geometry, no weather variability and no new collapse-induced opening. Recalculation of the 60 m east/west contrast from archived exposures gives 4.379466 dB. This is an internal effect of the imposed channel. The computational text and forest comparison make that scope explicit. The four named forest types cannot be assigned an empirical order on this basis. Old growth overlaps tropical and boreal and is not a mutually exclusive climate category.

Confounding and alternative evidence. A stand with greater observed event volume may have a different distribution of tree sizes, failure modes, wind loading and storm noise. A camera-confirmed fall is more likely in a gap or within line of sight than a deeply occluded understory collapse. Interference and distributed source orientation can resemble path loss. The protocol uses an independently surveilled footprint, weather logs, explicit indeterminate cases and separate calibrated-source transects. Natural sensitivity remains conditional on events visible by that independent apparatus. A residual crown gap can follow branch loss without whole-stem toppling. Independent silent imagery and explicit event definitions are essential; historically reconstructed images alone do not date a waveform to a second.

Unresolved ecological scope. Twelve plots and the proposed exposure duration offer no guaranteed number of large natural falls or independent storms. No field recruitment has occurred. Binomial power for randomized analogue trials is unrelated to power to detect a boreal-versus-tropical difference. With few storm blocks the protocol requires the event table, bounded missingness and uncertainty appropriate to the attained exposure. Data across plots may remain insufficient to infer a global efficiency, a forest-wide distribution of perceptual experiences, or a vanishing probability of radiation in rare geometries.

Cross-review revisions applied

The mechanics reviewer identified a missing experimental definition of an efficiency denominator, unstable three-dimensional localization in a shallow array, and possible reference-speaker directivity error. The field protocol now gives optical velocity and center-of-mass measurements, separates three efficiency ratios, specifies a scaled conditioning and uncertainty gate, retains failed localizations for occurrence analysis, and requires a reference-speaker directivity characterization. Those measures do not establish any field result in advance.

Information-theoretic review of the energy and inverse claims

Materials examined. Independent reading of the mechanics and source chapters, source-normalization and path definitions in the computational chapter, the forward and inverse implementations, declared parameters, posterior grid masses, error samples and energy summaries. I recomputed balance residuals, posterior mass sums, order–energy

ridge slope and the three median normalized mean-square errors with the Python standard library. This is an independent model-assisted reading of these materials. No field measurements enter it.

Mechanical balance. The simulated gravitational release minus resolved drag minus impact energy was 2.78×10^{-7} J. Rebound plus contact loss equaled impact energy at the precision of saved values. Of 38,957.935015 J assigned to contact loss, 0.38957935 J was allocated to radiation, leaving 38,957.545436 J for other loss. Emitted allocation divided by available release was 4.92978×10^{-6}, while the model parameter 10^{-5} was the fraction of *contact loss*. A reader summing the plotted bars would double count intermediate transfers. The accompanying text and caption assign each term to the appropriate level. Exact power normalization of a prescribed source does not independently measure physical efficiency. The unresolved empirical parameter remains so after the numerical checks.

External work. A definition using only positive external work must book the absolute value of any externally extracted work among the debits. Wind or a restraining support can perform negative work. The mechanics author corrected the sign convention in response to this review. A consistent net-work convention and a separate debit convention produce the same balance.

Exact degeneracy and its removal. The 80 Hz Rice likelihood depends on source energy scale E and excess filter order u only through $\sqrt{E}[1 + (80/125)^2]^{-u/2}$ with known multiplicative coefficients. Thus its constant-likelihood curves include an exact ridge with slope $d \log_{10} E/du = 0.1490958911$. Both grid posterior sums independently equaled one within 3×10^{-16}. A posterior marginal for each parameter on this ridge is shaped by the stipulated finite prior bounds. A weak ordinary posterior correlation alone would fail to diagnose the structural degeneracy. Complex multi-frequency data add shape and phase constraints in this two-parameter model. They would leave a residual exact gauge freedom if the frequency-independent path gain g were unknown, since $(g, E) \mapsto (g/k, k^2 E)$ preserves all complex predictions for any positive k. Absolute energy inference therefore needs independent calibration or a prior that carries the scale information.

Model-matched reconstruction. The median normalized squared errors across 160 saved noise draws were 4,516,063.6093 for direct inversion, 0.36461653 for regularization and 0.02708154 for projection onto the two-template subspace. The best method knows the source family and the propagation law used to generate the data. The second one uses shape information with a deliberate duration mismatch. Repeated draws quantify noise variability conditional on the same true waveform and model. No repeated survey of trees, empirical coverage of credible intervals across forests, or separation of ecological class labels follows from these figures. A norm over this waveform and a categorical accuracy on forest event labels answer different questions.

Unresolved discrimination. A large optimal matched-template separation can establish sensitivity of a particular controlled receiver. It cannot measure an event's Shannon information about arbitrary latent parameters. The recoverable information depends on the hypotheses, their priors and admissible observations. Even perfect identification of the fallen trunk does not give its airborne pressure history. An alternative source and path that yield equal pressure in the measured bands can remain indistinguishable; non-

acoustic residual evidence may or may not break the tie. The proposed field protocol can constrain these uncertainties; they cannot be resolved by increasing numerical precision in the present forward calculation.

Independent review of the event definition and boundary cases

Reviewed the lead chapter “The event and the proposition” and the independently authored chapter “Changing the conditions of production,” including every row of the verdict matrix. This is a methodological review from two disciplinary perspectives. It is an internal cross-read and supplies no external peer endorsement.

Auditory neuroscience

Strongest objection. A reconstruction based on presence, hearing status, or neural activation could appear to settle whether another subject experienced a tree-produced sound. Wakefulness, sleep, audiometric status, sensor activation, an orienting reaction and an auditory experience are different variables. In particular, clinically observed unresponsiveness is insufficient to establish a negative phenomenal result. Robust neural responses to auditory stimuli can persist during sleep [O7]. The distinction is decisive because the paper’s premise concerns whether anyone is around, while the conclusion concerns production.

Review result. The introductory chapter defines a subject-specific conscious percept separately from detection and storage. The boundary chapter explicitly distinguishes a stipulation of no consciousness from measured behavioral unresponsiveness. Its deaf-observer verdict conditions the answer on individual, band and route. The forest-without-auditory-organisms example allows plant tissue responses without inferring audition. These distinctions withstand the counterexamples. No cited neuroscience experiment observes the treefall subject’s inner state, and no threshold on pressure or cortical activity in the monograph certifies the presence or absence of phenomenal experience.

Weakest remaining assumption. “None” in the phenomenal column is justified only for the specified subject domain, site and time. Excluding nearby humans leaves possible nonhuman recipients and later or more distant arrivals. The matrix legend makes the stronger interpretation explicit. Unknown species-specific perception remains unknown where that stipulation is relaxed. A study attempting to resolve a particular animal case would need species-appropriate evidence separating auditory, visual and substrate cues. Even successful controlled discrimination would leave a further question about the animal’s phenomenology.

Philosophy of science

Strongest objection. A role can be inadvertently reified into a recorded object. The original ground-only matrix cell inferred that a record existed from the occurrence of a detection. A channel driving a momentary threshold indicator with no storage is a

counterexample. A microphone can also produce output without any archival subsystem. Earlier detection and later evidence require distinct truth conditions.

Disposition. The ground-only row now records detection while leaving retention unspecified. The unattended-microphone row and accompanying text require storage for a record. The absence-of-evidence row was also narrowed. Two compatible histories suffice to refute unique reconstruction of a trajectory. They need not make an observation uninformative about which history occurred. An event preferentially destroying its recorder would make the pattern of missing records itself informative. The no-update statement now requires equal likelihoods for the accessible observations under the hypotheses. These corrections were applied to the boundary chapter before final assembly.

Scope of the result. The source-side definition has an explicit subject, medium, causal contrast and interval. Changing a later interpretation while holding all physical causes fixed preserves the source solution by the uniqueness assumption. This establishes an invariance in the model and cannot test empirical claims beyond that model by relabeling identical histories. The matched-load recorder thought experiment helps separate the empirical question of device back-action from the semantic question of changing its role. For total silence evidence must address every radiating component in the full stated domain. A finite array that fails to detect the event does not establish unrestricted silence.

Unresolved issue. The generic affirmative is a theory-supported expectation with observational exemplars, not a population-frequency estimate. The anatomical and environmental passbands required for biological detection vary across subjects. The historical and philosophical alternatives do not disappear through calibration. In particular, a counterfactual disposition and a realized sensory episode can have different truth values for the same emission. No conclusion in these two chapters selects a unique metaphysics of sound by experimental fiat.

Independent review of propagation and experimental mechanics

Two disciplinary assessments were conducted by a separate computational agent from the author of the forest model and protocol. They constitute internal scientific criticism, without external peer review. The reviewers worked from the chapter drafts, proposed design, and archived numerical fields. No empirical trial was conducted.

Theoretical physicist’s assessment

Strongest objection. A computed field over rigid, flat ground is an exact solution of the wrong environment if presented as a measurement of a forest. The control omits refraction, curvature, trunks, soil leakage, foliage and motion of the source itself. It cannot establish numerical transfer coefficients for an old-growth plot or a rainforest. *Disposition:* the chapter identifies the exact boundary problem, marks the maps as a control, and provides testable stand-specific comparisons. Absolute site-specific transfer functions and shadow boundaries remain unmeasured. A useful future test is a calibrated source-height sweep along held-out transects with independent wind profiles, scored on

both direct arrival and late energy. Agreement on the early arrival alone does not validate scattered paths.

Field and sign audit. For time convention $e^{-i\omega t}$, differentiating e^{ikr}/r and dividing by $i\omega\rho$ gives radial velocity proportional to $p(1 + i/(kr))/(\rho c)$. The real and image sources cancel normal velocity on the plane. Directly integrating the far-zone squared pressure over the hemisphere gives relative powers 1.0048674662 and 0.9953592751 at 256 and 1,024 Hz respectively for a source 3 m above the plane. Identical prescribed source amplitude can therefore give different emitted power in free space and above the reflecting surface. A fixed-power comparison would require renormalization. *Disposition:* the model uses a fixed pressure-distance coefficient and explicitly excludes mechanical source feedback. A material tree does not generally hold this quantity fixed as the substrate changes.

Independent numerical check. A separate Python implementation computed the pressure sum, radial velocities, Cartesian active intensities, direct wavefront times and two-band SNR at all 154,481 points. The maximum absolute discrepancies in rms pressure, both intensity components and arrival time were zero at the available floating-point precision. The maximum SNR discrepancy was 3.56×10^{-15} dB, rounded upward. Code and output are in the supporting folder physics_review. These comparisons test numerical consistency within one specified analytic system. The separate hemisphere energy identity tests more than a duplication of field algebra. Neither estimates forest propagation error.

Counterexample and unresolved issue. A local plane-wave pressure notch can be very deep while the total event flux is positive. Conversely, a pressure antinode in a standing wave can have large exposure and very small active flux. One microphone cannot disambiguate these limits in the field. The chapter uses true vector intensity in the synthetic map and the protocol reserves absolute energy claims for intensity measurements around the source. The change from an ideal two-frequency steady state to an onset in a broadband, windy forest remains an open modeling error; no numerical forest shadow is a proof of physical absence.

Mechanical engineer's assessment

Strongest objection. A single pressure receiver can distinguish a release operation from a sham even if most of the detected signal arises from a changed fixture load. A release mechanism, support recoil and late substrate ringing can all correlate with the condition label. The substantiated quantity would be the acoustic difference caused by the entire intervention. *Disposition:* the primary endpoint is explicitly intervention discrimination; phased controls isolate actuator-only and contact-only components and a blinded truth arm separately examines natural trees. Physical equivalence of the analogue and a natural root–soil–crown failure remains unestablished. A compliant litter-covered landing and a stiff rock contact can have the same center-of-mass descent and radically different force spectra.

Mechanical denominator. Independently calibrated mass and descent can estimate gravity release in a guarded analogue. Impact energy additionally requires precontact

center-of-mass velocity, rotation if present, and a clear rule for stored energy or externally applied work. Contact-stage loss also depends on rebound and energy exported to the fixture, fragments and substrate. A measurement of force integrated at the soil is not the net aerodynamic impulse entering a compact acoustic dipole. *Disposition:* the revised protocol distinguishes the three denominators and specifies optical velocity, calibrated mass, substrate handling and the status of unmeasured terms. A natural tree's full air conversion efficiency remains unidentified without both a credible mechanical denominator and enclosure of its radiation. This objection does not invalidate the paired occurrence endpoint.

Event geometry and safeguards against overidentification. Four arrival times can be algebraically sufficient for three source coordinates and onset time but provide little redundancy; a nearly coplanar array makes height ill-conditioned and multipath can cause false arrival picks. A crown fracture several metres above ground followed by impact on soil also violates a shared point-source assumption. *Disposition:* the revised protocol specifies an explicit Jacobian conditioning screen, camera validation for four-arrival fits, and a near-ground fit only when independent evidence supports contact. Rejected localizations remain in the detection population. Source-reference calibration now records aperture, orientation and near-field limitations. The review cannot infer the underlying rupture height from a stable numerical optimizer.

Conservation and error budget. A finite pressure array on the ground perimeter leaves an open upper surface. A hemispherical air-energy measurement still needs the correct boundary flux if the ground absorbs incident or re-radiated energy. A near-source energy integral can include incoming reflections unless the window or directional separation is specified. Background subtraction can have signed cross terms. *Disposition:* the protocol distinguishes received exposure and signed background subtraction from net energy and requires independent radii, matched probes, solid-angle coverage and stated unmeasured flux for controlled energy claims. Residual uncertainty remains in directional coverage, sensor back-action, weather and the transferability of natural-event classifications. Retaining these limitations prevents a validated detector from being mistaken for a calorimeter.

Annotated literature and source records

The annotations identify the part of the argument each source supports and the limits of transfer to actual treefalls. Entries are grouped by their use in the study. Repeated sources retain local citation identifiers.

Independent verification

[A1] Acoustical Society of America, *Acoustical Terminology*, ANSI/ASA S1.1-2013, entry 2.01, "sound." The official entry distinguishes propagated oscillation and auditory sensation evoked by that oscillation. Its annotations mention structure-borne and underwater sound as well as tinnitus. Terminology entry

[A2] Marengo, E. A., and A. J. Devaney (2004). "Nonradiating sources with connections to the adjoint problem." *Physical Review E* 70, 037601. The publisher abstract establishes nonradiating volume-source results for linear differential operators. Article

[A3] Colton, D., J. Coyle, and P. Monk (2000). "Recent developments in inverse acoustic scattering theory." *SIAM Review* 42(3), 369–414. Theorem 4.1 establishes exterior uniqueness for a vanishing far field subject to the radiation and domain assumptions. Article text

[A4] NIST, *Digital Library of Mathematical Functions*, Chapter 10, §§10.49–10.52. Finite forms, Wronskians, derivative identities and limiting forms for spherical Bessel functions support the sphere calculation. Explicit forms · Wronskians · Derivatives · Limits

[A5] Neyman, J., and E. S. Pearson (1933). "On the problem of the most efficient tests of statistical hypotheses." *Philosophical Transactions of the Royal Society of London, Series A* 231, 289–337. Source for optimal simple-hypothesis tests at fixed false-alarm constraints. Publisher

[A6] Shannon, C. E. (1959). "Coding theorems for a discrete source with a fidelity criterion." *IRE International Convention Record* 7, Part 4, 142–163. Fidelity requires a defined source distribution and distortion measure. Reprint

Computational methods

[C1] Michiel J. W. Jansen. 1999. Analysis of variance designs for model output. *Computer Physics Communications* 117, 35–43. Publisher record. Verified the bibliographic record and article text. Source for squared-difference estimation of sensitivity components under independent design inputs. It supplies no distributions for trees or forest propagation.

[C2] S. O. Rice. 1945. Mathematical Analysis of Random Noise. *Bell System Technical Journal* 24, 46–156. Publisher record. Bibliographic record and original discussion of signal-plus-noise envelopes verified. The single-bin likelihood in the computational experiment follows by integrating its complex normal density over phase.

Forest acoustics and field validation

[F1] Price, M. A., Attenborough, K., and Heap, N. W. (1988). Sound attenuation through trees: Measurements and models. *Journal of the Acoustical Society of America* 84, 1836–1844. Field data at three British woodlands under neutral atmospheric conditions ground the comparison of ground, trunk and vegetation contributions. These measurements do not identify source efficiency for treefall. Source record

[F2] Padgham, M. (2004). Reverberation and frequency attenuation in forests—implications for acoustic communication in animals. *Journal of the Acoustical Society of America* 115, 402–410. Original transmission measurements in two Australian forests resolve distinct attenuation and reverberation patterns. Source record

[F3] Ellinger, N., and Hödl, W. (2003). Habitat acoustics of a neotropical lowland rainforest. *Bioacoustics* 13, 297–321. Measurements in southern Venezuela separate environmental acoustic transfer from the temporal and spectral variation of ambient sound. Source record

[F4] Van Renterghem, T., Huyghe, F., and Verheyen, K. (2021). Effect of tree species and season on the ability of forest floors to abate environmental noise. *Applied Acoustics* 184, 108349. Repeated common-garden impedance measurements in six broadleaved stands show a seasonal/moisture influence under the reported conditions. Source record

[F5] Albert, D. G. (2003). Observations of acoustic surface waves in outdoor sound propagation. *Journal of the Acoustical Society of America* 113, 2495–2500. Pulse waveforms and a height array over snow supplied evidence for a surface component. This study characterizes a boundary mechanism rather than a boreal forest in general. Source record

[F6] International Organization for Standardization (1993). *ISO 9613-1:1993, Acoustics—Attenuation of sound during propagation outdoors—Part 1: Calculation of the absorption of sound by the atmosphere.* Official scope and record. This reference concerns atmospheric absorption, separate from tree scattering and noise. Source record

[F7] Araujo, R. F., Grubinger, S., Celes, C. H. S., Negrón-Juárez, R. I., Garcia, M., Dandois, J. P., and Muller-Landau, H. C. (2021). Strong temporal variation in treefall and branchfall rates in a tropical forest is related to extreme rainfall: results from 5 years of monthly drone data for a 50 ha plot. *Biogeosciences* 18, 6517–6531. Primary independent canopy-disturbance observations in Panama. The time resolution limits event-specific acoustic attribution. Source record

[F8] International Electrotechnical Commission (2017). *IEC 60942:2017, Electroacoustics—Sound calibrators*. Official instrument-class specification. Reference to a conforming calibrator does not certify the complete deployed acquisition chain. Source record

[F9] Rhinehart, T. A., Chronister, L. M., Devlin, T., and Kitzes, J. (2020). Acoustic localization of terrestrial wildlife: Current practices and future opportunities. *Ecology and Evolution* 10, 6794–6818. A methods review of terrestrial localization, clock synchronization and deployment limitations. Source record

[F10] Sethi, S. S., Ewers, R. M., Jones, N. S., Signorelli, A., Picinali, L., and Orme, C. D. L. (2020). SAFE Acoustics: An open-source, real-time eco-acoustic monitoring network in the tropical rainforests of Borneo. *Methods in Ecology and Evolution* 11, 1182–1185. Primary deployment report supporting the engineering feasibility of unattended forest recording. Source record

Information, dissipation and causal structure

[I1] C. E. Shannon (1948). "A Mathematical Theory of Communication." *Bell System Technical Journal* 27, 379–423 and 623–656. Primary development of entropy, channel capacity and fidelity. The Gaussian channel calculation assumes a physically specified bandwidth and noise budget. Author's article, corrected reprint

[I2] Y. Polyanskiy and Y. Wu. *Information Theory*, 2024 prepublication text. Chapters on hypothesis testing and lower bounds for estimation, including the two-point method. Provides prior art for the overlap argument and its decision-theoretic interpretation. Author-hosted text

[I3] A. M. Stuart (2010). "Inverse problems: A Bayesian perspective." *Acta Numerica* 19, 451–559. Survey of inference for uncertain forward models, prior dependence and posterior stability. DOI

[I4] C. E. Shannon (1959). "Coding Theorems for a Discrete Source With a Fidelity Criterion." *IRE International Convention Record*, volume 7, part 4, 142–163. Primary development of rate-distortion coding for discrete sources. The scalar Gaussian formula used here is derived separately in the chapter. Reprint

[I5] A. N. Kolmogorov (1965). "Three Approaches to the Quantitative Definition of Information." Foundational treatment of algorithmic description of individual objects. The shortest-program quantity presupposes a choice of description language. Article

[I6] L. D. Landau and E. M. Lifshitz (1987). *Fluid Mechanics*, second edition. Chapter on thermal conduction, including section 49. Continuum entropy production and dissipative constitutive assumptions. Publisher

[I7] H. E. Bass, L. C. Sutherland and A. J. Zuckerwar (1990). "Atmospheric absorption of sound: Update." *Journal of the Acoustical Society of America* 88. Model includes oxygen and nitrogen relaxation in atmospheric absorption. This is a constitutive treatment and supplies no biome-wide coefficient. DOI

[I8] H. B. Callen and T. A. Welton (1951). "Irreversibility and Generalized Noise." *Physical Review* 83, 34. Primary fluctuation-dissipation treatment with a gas-pressure example. Equilibrium applicability matters for the environmental noise argument. DOI

[I9] M. Fink (1992). "Time reversal of ultrasonic fields. I. Basic principles." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 39, 555–566. Active capture and re-emission illustrate the access and control required for refocusing. DOI

[I10] G. E. Crooks (1999). "Entropy production fluctuation theorem and the nonequilibrium work relation for free energy differences." *Physical Review E* 60, 2721. Explicit

forward and reverse preparations under stochastic microscopically reversible dynamics. DOI

[I11] R. Landauer (1961). “Irreversibility and Heat Generation in the Computing Process.” *IBM Journal of Research and Development* 5, 183–191. Logical erasure and heat in computing devices. Its physical setup is distinct from generic energy loss in the atmosphere. DOI

[I12] A. D. O’Connell et al. (2010). “Quantum ground state and single-phonon control of a mechanical resonator.” *Nature* 464, 697–703. Empirical observation in an engineered mechanical mode; a demonstration of regime, with no extrapolation to the temperature of a forest. DOI

[I13] US National Institute of Standards and Technology (2024). *2022 CODATA Recommended Values of the Fundamental Constants of Physics and Chemistry*. Exact defining constants for the calculations of oscillator occupation and light travel time. NIST SP 959

[I14] W. H. Zurek (2003). “Decoherence, einselection, and the quantum origins of the classical.” *Reviews of Modern Physics* 75, 715. Environment-induced decoherence and the role of stable observables. DOI

[I15] M. Schlosshauer (published 2005 in volume 76). “Decoherence, the measurement problem, and interpretations of quantum mechanics.” *Reviews of Modern Physics* 76, 1267. Clarifies the explanatory scope and limits of the reduced-state argument. DOI

[I16] J. Faye (revised 2024). “Copenhagen Interpretation of Quantum Mechanics.” *Stanford Encyclopedia of Philosophy*, summer 2025 archive. Distinguishes historically different doctrines associated with this label. Archived entry

[I17] H. Everett III (1957). “ ‘Relative State’ Formulation of Quantum Mechanics.” *Reviews of Modern Physics* 29, 454. Primary account of relative states and measurement. DOI

[I18] C. Rovelli (1996). “Relational Quantum Mechanics.” *International Journal of Theoretical Physics* 35. Physical systems supply the relata. The author’s revised preprint explicitly states their equivalence with respect to observation. Author’s manuscript

[I19] G. C. Ghirardi, A. Rimini and T. Weber (1986). “Unified dynamics for microscopic and macroscopic systems.” *Physical Review D* 34, 470. Primary dynamical-collapse proposal with empirically meaningful modifications to unitary dynamics. DOI

[I20] W. H. Zurek (2009). “Quantum Darwinism.” *Nature Physics* 5, 181–188. Information about system observables in environmental fragments. No measured redundancy for a falling tree is supplied. DOI

[I21] C. Barceló, S. Liberati and M. Visser (2011 revision). “Analogue Gravity.” *Living Reviews in Relativity* 14, 3. Acoustic characteristics and the restrictions on an effective acoustic metric in a moving fluid. DOI

[I22] A. Einstein (1905). “Zur Elektrodynamik bewegter Körper.” *Annalen der Physik*. Primary treatment of synchronization, frame dependence and Lorentz transformations. English translation

Mechanics and acoustic radiation

[M1] M. P. Coutts (1986). Components of tree stability in Sitka spruce on peaty gley soil. *Forestry* 59, 173–197. Controlled pulling and sequential interventions distinguish several anchorage contributions. The tree, loading rate and specific soil limit transfer to free collapse. Publisher and DOI.

[M2] M. P. Coutts (1983). Root architecture and tree stability. *Plant and Soil* 71, 171–188. Field observations, including buried microphones timing root breakage, relate anchorage and rupture. A buried transducer does not measure total airborne radiation. Publisher and DOI.

[M3] T. Lundström, M. J. Jonsson, A. Volkwein and M. Stoffel (2009). Reactions and energy absorption of trees subject to rockfall: a detailed assessment using a new experimental method. *Tree Physiology* 29, 345–359. Impacts into fifteen standing spruces reveal local loading and subsequent distributed energy absorption. This reverses the experimental roles of tree and projectile relative to a tree falling on soil. Indexed article. DOI.

[M4] B. Theckes, E. de Langre and X. Boutillon (2011). Damping by branching: a bioinspiration from trees. *Bioinspiration & Biomimetics* 6, 046010. Mechanical modeling of branched structures establishes geometry-dependent energy transfer among modes. Distinguish transfer to daughter modes from final dissipation in them. Indexed article. DOI.

[M5] C. A. Senalik and B. Farber (2021). Mechanical properties of wood. Chapter 5 of *Wood Handbook: Wood as an Engineering Material*, USDA Forest Products Laboratory, FPL-GTR-282. Engineering synthesis and material-property reference. Specimen axes, moisture, defects and test geometry matter to extrapolation. Chapter index. Handbook DOI.

[M6] S. Vasic and I. Smith (2002). Bridging crack model for fracture of spruce. *Engineering Fracture Mechanics* 69, 745–760. In situ microscopy of spruce specimens and a model of crack bridging support a process-zone treatment of fracture work. Publisher and DOI.

[M7] A. Kerimov, G. Mavko, T. Mukerji and J. Dvorkin (2018). Static and dynamic effective moduli of elastic-perfectly plastic granular aggregates. Stanford meeting presentation, slide 4. Secondary check of the modulus, radius and exponent in the conventional elastic spherical-contact law. No soil or tree contact parameter is inferred from it. Equation and geometry.

[M8] ISO 9614-1:1993. *Acoustics — Determination of sound power levels of noise sources using sound intensity — Part 1: Measurement at discrete points*. Official description of the enclosing-surface intensity method. An irregular outdoor transient requires an additional measurement design. Standard record.

[M9] M. J. Lighthill (1952). On sound generated aerodynamically I. General theory. *Proceedings of the Royal Society A* 211, 564–587. Primary derivation of the quadrupole stress formulation. Identities and flow approximations are distinguished in the text. Publisher and DOI.

[M10] N. Curle (1955). The influence of solid boundaries upon aerodynamic sound. *Pro-*

ceedings of the Royal Society A 231, 505–514. Primary extension of the acoustic analogy to include solid boundary loading. Publisher and DOI.

[M11] J. E. Ffowcs Williams and D. L. Hawkings (1969). Sound generation by turbulence and surfaces in arbitrary motion. *Philosophical Transactions of the Royal Society A* 264, 321–342. Primary moving-surface acoustic analogy gives conditions on compact reductions. Publisher and DOI.

[M12] R. E. Musafir (2013). On non-radiating sources. *Journal of Sound and Vibration* 332, 3947–3955. Primary mathematical analysis of source distributions producing the same exterior field and the relation to inverse-source ambiguity. Publisher and DOI.

[M13] D. Colton (2003). Inverse acoustic and electromagnetic scattering theory. *Inside Out: Inverse Problems*, MSRI Publications 47, 67–110. Theorem 3.1 gives Rellich's lemma for zero far field. The normal-velocity corollary uses this established result. Author chapter.

[M14] ISO 9613-1:1993. *Acoustics — Attenuation of sound during propagation outdoors — Part 1: Calculation of the absorption of sound by the atmosphere*. Official scope and climatic variables of the pure-tone absorption calculation. Its empirical domain must be checked before extension to infrasonic or ultrasonic bands. Standard record.

Audition, scientific terminology, and the historical question

[O1] Acoustical Society of America, Acoustical Terminology, §2.01, "sound." The normative entry specifies propagated oscillations and evoked sensation and explicitly discusses the dissociation. ASA definition.

[O2] National Institute on Deafness and Other Communication Disorders, "How Do We Hear?" Institutional account of air conduction, middle ear, cochlea and auditory nerve. NIDCD.

[O3] Lincoln Gray, "Auditory System: Pathways and Reflexes," *Neuroscience Online*, section 2, chapter 13. Central connections, bilateral projections and parallel processing. University of Texas.

[O4] A. J. Hudspeth (2014), "Integrating the active process of hair cells with cochlear function," *Nature Reviews Neuroscience* 15, 600–614. Review on active mechanics and frequency selection. DOI 10.1038/nrn3786.

[O5] J. Zheng et al. (2000), "Prestin is the motor protein of cochlear outer hair cells," *Nature* 405, 149–155. Primary investigation identifying a molecular contributor to outer hair-cell motility. DOI 10.1038/35012009.

[O6] S. Safieddine, A. El-Amraoui and C. Petit (2012), "The auditory hair cell ribbon synapse: from assembly to function," *Annual Review of Neuroscience* 35, 509–528. Graded inner hair-cell potentials and transmitter release onto afferents. DOI 10.1146/annurev-neuro-061010-113705.

[O7] H. Hayat et al. (2022), "Reduced neural feedback signaling despite robust neuron and gamma auditory responses during human sleep," *Nature Neuroscience* 25, 935–943. Intracranial recordings discriminate sleep-state effects across several response

measures; individual conscious experience was not read out by this method. DOI 10.1038/s41593-022-01107-4.

[O8] D. Raveh and N. Lavie (2015), “Load-induced inattentional deafness,” *Attention, Perception, & Psychophysics* 77, 483–492. Behavioral detection depends on competing visual task load. DOI 10.3758/s13414-014-0776-2.

[O9] National Institute on Deafness and Other Communication Disorders, “Tinnitus.” Distinction between subjective sound perception and an external source. NIDCD.

[O10] D. J. M. Kraemer, C. N. Macrae, A. E. Green and W. M. Kelley (2005), “Musical imagery: sound of silence activates auditory cortex,” *Nature* 434, 158. Primary functional-imaging investigation of silent gaps in music. DOI 10.1038/434158a.

[O11] G. Menda et al. (2019), “The Long and Short of Hearing in the Mosquito *Aedes aegypti*,” *Current Biology* 29, 709–714.e4. Behavioral and physiological tests of the insect’s airborne auditory reception. DOI 10.1016/j.cub.2019.01.026.

[O12] N. J. Lindsey, H. Rademacher and J. B. Ajo-Franklin (2020), “On the Broadband Instrument Response of Fiber-Optic DAS Arrays,” *Journal of Geophysical Research: Solid Earth* 125, e2019JB018145. Empirical comparison with calibrated seismometry and analysis of installation response. DOI 10.1029/2019JB018145.

[O13] H. M. Appel and R. B. Cocroft (2014), “Plants respond to leaf vibrations caused by insect herbivore chewing,” *Oecologia* 175, 1257–1266. Primary evidence for response to selected leaf vibrations; no treefall or consciousness endpoint. DOI 10.1007/s00442-014-2995-6.

[O14] D. T. Kemp (1978), “Stimulated acoustic emissions from within the human auditory system,” *Journal of the Acoustical Society of America* 64, 1386–1391. Direct evidence of acoustic emission from a sensory apparatus. DOI 10.1121/1.382104.

[O15] Aristotle, *De Anima*, II.8 and III.2, in the J. A. Smith translation. The passages discuss actual and potential sound and the relation between activities of sensing and sensed. Book II and Book III.

[O16] John Locke, *An Essay Concerning Human Understanding*, Book II, chapter VIII, especially §§10–15. Primary historical source on powers of bodies and ideas of secondary qualities. Text.

[O17] George Berkeley (1710), *A Treatise Concerning the Principles of Human Knowledge*, part I, §§3, 6, 23, 29–33. Unperceived study, imagined trees and the dependence of ideas; compare the scholarly overview for interpretations of divine agency. Primary text and Stanford Encyclopedia of Philosophy.

[O18] *Eastern State Journal* (White Plains, NY), 6 May 1853, p. 1, col. 4. Digitized primary newspaper, masthead and item reporting a lyceum debate on whether an unheard falling tree makes a noise. The wording establishes attested use, not authorship. Contemporary newspaper page.

[O19] Ben Zimmer (22 August 2020), American Dialect Society mailing list, “If a tree falls…” Gives the location of the White Plains newspaper and credits Jonathan Lighter’s Vermont antecedent; the thread includes additional citations from Garson O’Toole. Archival

discovery credit and search trail. ADS-L.

[O20] “Editor’s Table,” question 3, *The Chautauquan* III(9), June 1883, pp. 543–544. Primary facsimile checked across page break. Island formulation excluding people; answer invokes sound perception by auditory sense organs. Facsimile.

[O21] *Scientific American* 50(14), 5 April 1884, p. 218, question 18 from S. A. H. Primary issue reproduction distinguishing air vibration from sensory recognition. Issue.

[O22] Casey O’Callaghan (2007), *Sounds: A Philosophical Theory*. Oxford University Press. Primary theoretical source on sound-making events involving a body and a medium. DOI 10.1093/acprof:oso/9780199215928.001.0001.

[O23] Roberto Casati, Jérôme Dokic and Elvira Di Bona, “Sounds,” *Stanford Encyclopedia of Philosophy*, substantive revision 2020. Competing distal, medial, proximal and aspatial accounts; differences among located-event and relational-event theories. Entry.

[O24] *Stanford Encyclopedia of Philosophy*, “Scientific Realism” and “Physicalism.” These philosophical positions concern different commitments. Neither alone chooses between stimulus and evoked sensation as the referent of “sound.” Scientific realism and physicalism.

[O25] *Stanford Encyclopedia of Philosophy*, “The Problem of Perception.” Survey of philosophical accounts of perception and its objects; used to distinguish direct acquaintance from causal mediation and sense-data accounts. Entry.

[O26] John Stuart Mill (1865), *An Examination of Sir William Hamilton’s Philosophy*, chapter XI. The chapter develops the account of enduring possibilities of sensation. Collected Works, vol. IX.

[O27] *Stanford Encyclopedia of Philosophy*, “Operationalism.” Scholarly treatment of P. W. Bridgman’s 1927 program and the stronger interpretations subsequently assigned to it. Entry.

Case records and angular sampling

[R1] National Park Service. *Acoustic Monitoring Site: Rainbow Loop Trail*, North Cascades National Park. Deployment dated July 2009; page updated August 11, 2017. The catalog lists “Tree fall” and displays a spectrogram. The web figure provides neither a calibrated source level nor proof of human absence. Site record.

[R2] Jasper Ridge Biological Preserve, Stanford University. *Annual Report 2006*, p. 23. Reproduces the Jasper Ridge station seismic trace associated with a large eucalyptus falling in Woodside on the night of July 8, 1995, local time (July 9 UTC). The seismic channel cannot identify the radiated acoustic energy. Primary report.

[R3] Mass, Clifford F., Robert Conrick, Nicholas Weber and Joseph P. Zagrodnik. “The Quinault Blowdown: A Microscale Wind Event Driven by a Mountain-Wave Rotor.” *Bulletin of the American Meteorological Society* 100 (2019). Strong impulses during the January 2018 storm were attributed probabilistically to large treefalls. Aerial and ground surveys provided independent evidence of tree damage. DOI.

[R4] Reznick, Bruce. “Some constructions of spherical 5-designs.” *Linear Algebra and its Applications* 226–228 (1995), 163–196. Defines exact angular cubature and reviews the 12-point icosahedral design. Underlies the quadratic far-field sampling example. Publisher.

[R5] Acoustical Society of America. *Acoustical Terminology*, §2.01, “sound.” Normative vocabulary allows both mechanical propagation and auditory sensation evoked by that propagation. Its examples distinguish structure-borne and airborne sound. Standards terminology.

[R6] Marengo, Edwin A. and Anthony J. Devaney. “Nonradiating sources with connections to the adjoint problem.” *Physical Review E* 70 (2004), 037601. Gives an adjoint orthogonality condition for localized nonradiating sources in linear equations. This is a prior result, not a demonstration of a naturally nonradiating tree. DOI.

Final verdict

Meaning assigned to “makes a sound”	Verdict under the stated absence condition
Source event	Yes for an ordinary sounding collapse involving moving material and a supporting medium. Individuating several snaps as one crash is a separate convention.
Propagating airborne oscillation	Yes under ordinary radiating motion in air. In a true vacuum there is no airborne mode. Presence of a subject is irrelevant to this condition.
Propagating mechanical oscillation in any supporting medium	Yes when the fall excites such a mode in wood, soil, air or water. Removing the gas alone does not remove solid waves.
Positive outward acoustic energy	Yes under the specified boundary-source theorem. Quasistatic limits, additional sources, absorbing boundaries and domain choices preclude an unrestricted lower bound.
Sound accessible to a possible listener	Conditional on a realizable receiver, placement, bandwidth, background and allowed intervention. No actual listener is required for a disposition.
Successful biological detection	No when the premise excludes all suitable organisms. If “nobody” excludes only people, the premise leaves nonhuman detection open.
Evoked conscious auditory experience	No if every eligible subject is absent through the relevant arrival interval. Human absence alone does not determine another animal’s experience.
Artificial detection or durable recording	Contingent on equipment, coupling, operation, classification and storage. No person need attend the recording.
Information in the acoustic field	Potentially positive when the distribution of field observations differs across specified source alternatives. A receiver need not actually read it.
Operational certification or historical knowledge	Depends on the test, available evidence and target. A ground trace can support occurrence without recovering an airborne waveform.
Realist or physicalist reading	A propagated disturbance can be objectively instantiated. Physicalism can also treat sensation as a distinct physical process requiring a suitable organism.
Dispositional or phenomenalist reading	A relevant possible experience can remain available in a world without a present subject, depending on the counterfactuals allowed.

Meaning assigned to “makes a sound”	Verdict under the stated absence condition
Experience-constituted reading	Making a sound in the sense of actually producing an experience requires a subject. Broader idealism has several accounts of unperceived objects and gives no single verdict from the word alone.

A single binary answer valid under all these readings is unavailable. An answer to the ordinary production question is nonetheless warranted. Exposed motion and impact transfer mechanical energy, and propagating oscillations in the air qualify as sound in standard physical usage. Removing listeners does not remove those production mechanisms. In a particular historical case the inference can remain uncertain. In an unusual environment the material channel itself can be absent. Neither qualification changes what an ordinary falling tree does.

Yes, in ordinary woods a falling tree makes sound whether anyone is there to hear it.