Sharp length–inradius bounds and heat-content stability on compact metric graphs

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Luminary Oddities

Abstract

We determine how total length and Dirichlet inradius constrain heat retention on compact metric graphs, refining the all-times length-only comparison with the mixed Dirichlet–Neumann interval proved in a companion paper. For every stationary p-torsion problem, $1 < p < \infty$, we obtain the exact joint upper envelope, and we determine the sharp envelope of every positive linear resolvent. For finite metric trees with one Dirichlet root, the same endpoint-mass interval gives the exact heat-content supremum at every positive time; one sequence of finite brooms approaches the entire envelope uniformly on positive compact time windows. The resulting marked measured geometric stability estimate has the optimal exponent $1/3$, uniformly in tree complexity and minimum edge length. A positive averaged mass-relocation principle extends the heat comparison to trees with matching edge energy and speed weights at least one, and to cyclic graphs with exact root-preserving tree quotients, where the resistance height of the quotient sharpens the envelope. For general compact graphs, we prove every geometric Hölder exponent below $1/3$, while a cubic pitchfork asymptotic excludes every exponent above it. The proofs combine shortest-path variational bounds, positive absorption-time response identities and a nonnegative heat-deficit source.

1 Introduction

How much heat can a graph retain when both its total length and its largest distance from the absorbing boundary are prescribed? The total length alone singles out the interval with one reflecting and one absorbing endpoint. Keeping the Dirichlet inradius adds information about how the graph departs from that interval. We determine the sharp stationary and resolvent envelopes for these two geometric parameters, and use their deficits to quantify the geometry of near-maximal heat retention at a single positive time.

The model and the sharp envelopes

Let G be a finite compact connected metric graph of total length $L > 0$, with a nonempty set D of Dirichlet vertices. At all other vertices we impose continuity and the unweighted Kirchhoff condition; an unmarked terminal vertex is therefore reflecting. Loops and multiple edges are allowed, and $G \setminus D$ need not be connected. Let H_G be the nonnegative Dirichlet–Kirchhoff Laplacian and write

$$R = \max_{x \in G} \operatorname{dist}(x, D), \qquad \mathcal{Q}_G(t) = \langle \mathbf{1}, e^{-tH_G}\mathbf{1} \rangle.$$

Integration and the inner product use arclength measure. The comparison interval I_L has length L, with one Dirichlet and one Neumann endpoint. The weak operator formulations and the geometric distance used below are defined in the corresponding proof sections.

Bifulco and Täufer [1] asked whether $\mathcal{Q}_G(t) \le \mathcal{Q}_{I_L}(t)$ at every time. For $G \setminus D$ connected, they proved it for large times and, when the edge lengths are rationally dependent, for small

times [1, Theorem 2.6], and they recorded the all-times question in their abstract and in [1, Remark 2.9]. The companion paper [A, Theorem 1.2] proves the inequality for every graph in the present model at every time, with no condition on the edge lengths; the decomposition at Dirichlet vertices recorded in [2, Remark 2.7] also accommodates disconnected $G \setminus D$. Theorem 5.3 below rederives it for initial datum one through a nonnegative heat-deficit source, whose quantitative form the stability theory requires. This all-times inequality uses only the total length. Prescribing the Dirichlet inradius as well, we determine the exact supremum at every positive time on rooted trees,

$$\mathcal{Q}_T(t) \le Q_{R,L-R}(t) < \mathcal{Q}_{I_L}(t) \qquad (t > 0,\ R < L),$$

where $Q_{R,L-R}$ is the endpoint-mass interval model described below. The supremum is approached by finite brooms uniformly on positive compact time windows. The pitchforks singled out in [1, Remark 2.8] as the delicate small-time candidates obey the comparison at every time through an explicit positive convolution formula (Proposition 9.1, also [A, Proposition 6.1]). At fixed positive times their deficit is exactly cubic in the arm length (Theorem 10.1), which fixes the optimal geometric stability exponent 1/3. The double-Dirichlet counterpart of the domain comparison discussed in [1, Remark 2.7] is the subject of [A, Theorem 5.1], under the condition that every bridge has Dirichlet vertices on both sides.

For $1 < p < \infty$, let u_p solve the datum-one stationary problem $-(|u_p'|^{p-2}u_p')' = 1$, with zero Dirichlet values and natural Kirchhoff p-flux conditions, and put

$$S_p(G) = \int_G u_p \, \mathrm{d}x, \qquad q = \frac{p}{p-1}.$$

Our first sharp envelope is

$$S_p(G) \le \frac{L^{q+1} - (L-R)^{q+1}}{q+1}. \tag{1}$$

The normalization is important: S_p is the torsion integral, not its $(p-1)$st power. In particular $S_2(I_L) = L^3/3$. At each prescribed $0 < R < L$, the right-hand side is an exact supremum. It is approached by finite brooms and is not attained by a finite graph. We prove the full weak formulation, the bound, nonattainment and the fixed-parameter sharpness in Section 2.

The second envelope retains a positive resolvent parameter. Set $J_G(z) = \langle \mathbf{1}, (H_G + z)^{-1}\mathbf{1} \rangle$ for $z > 0$ and $s = \sqrt{z}$. Then

$$J_G(z) \le \frac{L}{z} - \frac{\tanh(sR) + s(L-R)}{z^{3/2}\big(1 + s(L-R)\tanh(sR)\big)}. \tag{2}$$

This is again the exact supremum at fixed L, R, approached by the same broom limit. Section 3 proves the bound and an exact integral formula for its deficit from $J_{I_L}(z)$. The stationary $p = 2$ bound is recovered as $z \downarrow 0$. The resolvent family supplies additional information needed for the heat-stability argument. On rooted trees and exact tree quotients, the pointwise heat comparison with the limiting broom model is obtained separately, through positive inverse kernels (Section 7).

From deficit to marked measured geometry

Normalize length by L and arclength measure by L^{-1}, and put $\beta = 1 - R/L$. We compare G/L with the unit mixed interval by a common-embedding distance d_m. This distance records the metric support, the Dirichlet marked set and the arclength probability measure through Hausdorff and Prokhorov distances. Thus it detects more than an unmarked metric approximation. The shortest-path argument gives

$$d_m(G/L, I_1) \le 2\beta.$$

Combined with (1), it yields

$$d_m(G/L, I_1) \le 2\left(\frac{L^{q+1} - (q+1)S_p(G)}{L^{q+1}}\right)^{1/(q+1)}. \tag{3}$$

The exponent $1/(q+1)$ is optimal, even on a fixed graph topology; the coefficient 2 comes from an explicit common embedding. The distance and the proof of geometric stability are given in Section 4.

For heat content, the normalized one-time deficit is

$$\delta_G(\tau) = \frac{\mathcal{Q}_{I_L}(L^2\tau) - \mathcal{Q}_G(L^2\tau)}{L}.$$

For every $\varepsilon > 0$ and every window $0 < \tau_0 \le \tau_1 < \infty$, we prove

$$\delta_G(\tau) \ge C_{\varepsilon,\tau_0,\tau_1}\beta^{3+\varepsilon} \qquad (\tau \in [\tau_0, \tau_1]), \tag{4}$$

where the constant is positive and independent of the number of edges, vertices and minimum edge length. Consequently, for each $0 < \alpha < 1/3$ there is a uniform estimate

$$d_m(G/L, I_1) \le C_{\alpha,\tau_0,\tau_1}\delta_G(\tau)^{\alpha}.$$

For general graphs the positive-time proof uses a nonnegative heat-deficit source to control an earlier integrated deficit, followed by the sharp resolvent reserve and a weighted-tail estimate. The necessary comparison and source identities for constant initial datum are proved inside this article; they overlap with [A, Sections 3 and 4], as detailed at the start of Section 5.

A family of small-arm pitchforks shows that the heat deficit is cubic in its geometric departure from the interval. The full asymptotic is proved in Section 10, uniformly on positive compact time windows. It rules out every exponent $\alpha > 1/3$, even at a fixed positive observation time. Together with the preceding upper stability bounds, this identifies $1/3$ as the exact supremum of the admissible exponents. For singly rooted trees, the endpoint itself is valid by the stronger heat-envelope comparison below.

The sharp tree heat envelope and its positive extensions

For a finite tree with one Dirichlet root, the positive-time comparison retains both geometric parameters exactly. Let $Q_{r,\beta}$ be the heat content on $[0, r]$ with Dirichlet condition at zero, energy $\int |f'|^2$ and speed measure $\mathrm{d}x + \beta\delta_r$; its initial heat includes the endpoint atom. We prove

$$\mathcal{Q}_T(t) \le Q_{R,L-R}(t) \qquad (t > 0).$$

At every prescribed $0 < R < L$ this is the exact supremum, approached by the same finite brooms uniformly on positive compact time windows. Each finite tree has strict inequality there; the DN interval attains the case $R = L$. The endpoint model has a positive radius-variation formula, which yields a cubic deficit and hence the optimal admissible geometric exponent $1/3$ for this tree class.

The proof uses absorption-time distributions to merge parallel rooted branches, and positive junction-response factors to propagate their heat-content order along a common stem. An averaged mass-relocation lemma then moves excess speed mass from ancestors to descendant leaves. In resistance coordinates this gives the same heat envelope for weighted trees whose edge energy and speed have identical multiplicities $c_e \ge 1$. Exact invariant tree quotients transfer the result to a specified cyclic class; equilateral complete graphs with one Dirichlet vertex provide examples of unbounded cycle rank. These results are proved in Section 7.

Relation to existing bounds and methods

Mugnolo and Plümer [4] establish the sharp length-only stationary bound $S_2(G) \le L^3/3$ and discuss bounds retaining the Dirichlet inradius, including $S_2(G) < RL^2$ [4, Remark 5.2(1)]. Our joint envelope (1) for $p = 2$ is strictly smaller than RL^2 when $0 < R < L$, and determines the exact supremum rather than an inradius scaling alone. Their stower constructions also supply important ancestry for concentrating graph length in short arms; their explicit stower formula already yields torsion of order R at fixed length, incompatible with an upper bound proportional to LR^2 (see the discussion after Corollary 2.4). The new ingredient here is the exact joint envelope. Their work also develops surgery principles and Kohler–Jobin-type bounds for the ground-state energy.

Özcan [5] develops sharp metric-graph p-torsion inequalities using level sets and variational methods. Comparisons with that work must account for the powered convention for torsional rigidity: our quantity is S_p, and the corresponding powered quantity is S_p^{p-1}. The extension here determines the exact joint length–inradius envelope and its fixed-parameter sharpness for every $1 < p < \infty$. The linear resolvent theorem and the positive-time stability conclusions concern the linear case $p = 2$.

For heat content, Bifulco and Täufer [1] prove the interval comparison for large times and, under rational dependence of the edge lengths, for small times, and give an all-times comparison formula for suitable pairs of equilateral graphs [1, Corollary 4.9]. Bifulco and Mugnolo [2] give a closed formula for the heat content at every positive time as a sum over paths between Dirichlet vertices, a small-time expansion, and surgery principles, including operations that preserve heat content at all times. The companion paper [A] proves the length-only all-times comparison, together with a concentration order for general nonnegative L^2 data. The present question is quantitative: how much does prescribed inradius reduce the extremal stationary and resolvent values, and how does a small positive-time deficit constrain marked measured geometry? The sharp envelopes, effective heat reserve and cubic obstruction answer successive parts of that question.

The analytic inputs have classical antecedents. Friedlander's graph coarea argument [3] and parabolic symmetrization [6, 7, 8] underlie the constant-datum heat comparison, here and in [A]. Our proofs retain the graph-specific positive deficit source and the shortest-path variational information needed for stability. The paper first proves the stationary and resolvent envelopes and their geometric consequence. It then supplies the necessary heat-source argument, the exact rooted-tree heat envelope and its mass-relocation extensions, the general-graph effective positive-time estimate, and the sharpness obstruction.

2 Sharp stationary bounds in length and inradius

Let G be a finite compact connected metric graph with strictly positive edge lengths, total length $L > 0$, and a nonempty set D of Dirichlet vertices. Integrals use ordinary edge-length measure. All functions are continuous at vertices; at vertices outside D we impose the natural Kirchhoff condition. In particular, a degree-one vertex outside D has a Neumann condition. The Dirichlet inradius is

$$R = \max_{x \in G} \operatorname{dist}_G(x, D), \qquad 0 < R \le L.$$

There is no bound on the number of edges or the vertex degrees.

Fix $1 < p < \infty$ and put $q = p/(p-1)$. Write $V_p(G, D)$ for the continuous, edgewise $W^{1,p}$ functions vanishing on D. We use the unpowered normalization

$$S_p(G, D) = \int_G u_p \, \mathrm{d}x,$$

where u_p is the weak solution of

$$\int_G |u_p'|^{p-2}u_p' f' \,\mathrm{d}x = \int_G f \,\mathrm{d}x \qquad (f \in V_p(G,D)). \tag{5}$$

Thus the edge equation is $-(|u_p'|^{p-2}u_p')' = 1$, with conservation of outward p-flux at every non-Dirichlet vertex.

The length-only Saint–Venant comparison is classical for $p = 2$ [4] and has a nonlinear counterpart in [5]. The latter uses the powered quantity $\mathcal{T}_p = S_p^{p-1}$. We retain S_p throughout the stationary argument and give the conversion explicitly below. The new comparison fixes both L and R.

Lemma 2.1 (Weak problem and normalization)**.** *The problem* (5) *has a unique nonnegative, nonzero solution. Moreover*

$$S_p(G,D) = \int_G |u_p'|^p \,\mathrm{d}x, \tag{6}$$

$$S_p(G,D) = \frac{1}{p-1} \sup_{f \in V_p(G,D)} \left\{ p\int_G f \,\mathrm{d}x - \int_G |f'|^p \,\mathrm{d}x \right\}, \tag{7}$$

$$\mathcal{T}_p(G,D) := \sup_{0 \neq f \in V_p(G,D)} \frac{|\int_G f \,\mathrm{d}x|^p}{\int_G |f'|^p \,\mathrm{d}x} = S_p(G,D)^{p-1}. \tag{8}$$

Proof. For any $x \in G$, integrate f' along a simple path from D to x. Hölder's inequality gives

$$|f(x)| \le L^{1/q} \left(\int_G |f'|^p \,\mathrm{d}x \right)^{1/p}.$$

Consequently the derivative norm controls the full Sobolev norm on $V_p(G,D)$. This space is a closed subspace of the finite product of the edge Sobolev spaces. The functional

$$f \longmapsto \frac{1}{p}\int_G |f'|^p \,\mathrm{d}x - \int_G f \,\mathrm{d}x$$

is coercive and weakly lower semicontinuous. Reflexivity gives a minimizer, and strict convexity in derivatives, together with the Dirichlet anchor, gives uniqueness. Its Euler equation is (5). Replacing a real minimizer by its absolute value preserves energy and does not increase the functional, so uniqueness gives nonnegativity. A small positive multiple of a nonzero nonnegative edge-interior bump has negative functional value; hence the minimizer is nonzero.

On an edge its p-flux has distributional derivative -1, so that flux is affine. Inverting the map $t \mapsto |t|^{p-2}t$ gives a continuous edge derivative. Testing with functions having prescribed vertex values yields the Kirchhoff flux law. No twice-differentiability assertion at a zero of u_p' is needed.

Testing by u_p proves (6). The minimized functional at u_p equals $-(p-1)S_p/p$, proving (7). Finally (5) and Hölder give

$$\left| \int_G f \,\mathrm{d}x \right| \le S_p^{(p-1)/p} \left(\int_G |f'|^p \,\mathrm{d}x \right)^{1/p}.$$

Equality in the resulting quotient bound is attained by $f = u_p$, which proves (8). □

Theorem 2.2 (Sharp joint stationary envelope)**.** *For every graph in the stated class and every* $1 < p < \infty$*,*

$$S_p(G,D) \le A_p(L,R) := \frac{L^{q+1} - (L-R)^{q+1}}{q+1}. \tag{9}$$

For each prescribed $0 < R < L$*, the right side is the exact supremum over finite graphs with those values of* L, R*, but is not attained by a finite graph. At* $R = L$ *the Dirichlet–Neumann interval attains the bound. In the powered convention the inequality is* $\mathcal{T}_p(G,D) \le A_p(L,R)^{p-1}$*.*

Proof. The supremum in (7) may be restricted to nonnegative real functions. Let f be such a function, not identically zero, and choose a point x where it reaches its maximum. A shortest path γ from a closest Dirichlet vertex to x has length $r = \operatorname{dist}_G(x, D) \le R$. It is simple and has edge measure r; if x lies inside an edge we subdivide that edge. Parameterize it by arclength from its Dirichlet endpoint and put $g = f|_\gamma$. Then $g(0) = 0$ and $g(r) = \max_G f$. The complement has length $L - r$, whence

$$\begin{aligned} p\int_G f \,\mathrm{d}x - \int_G |f'|^p \,\mathrm{d}x &\le p\int_0^r g(s)\,\mathrm{d}s + p(L-r)g(r) - \int_0^r |g'(s)|^p \,\mathrm{d}s \\ &= \int_0^r \left[p(L-s)g'(s) - |g'(s)|^p\right] \mathrm{d}s. \end{aligned}$$

The equality is Fubini's formula for an absolutely continuous g with $g(0) = 0$; it requires no monotonicity of g. For $a \ge 0$ and real z,

$$paz - |z|^p \le (p-1)a^q.$$

Applying this sharp Young inequality pointwise gives an upper bound $(p-1)\int_0^r (L-s)^q \,\mathrm{d}s$, and then $(p-1)\int_0^R (L-s)^q \,\mathrm{d}s$. Equation (7) proves (9).

If $R < L$, apply the argument to u_p. The complement of its selected path has positive length and contains an open edge subinterval. Equality would force the discarded energy there to be zero, so u_p would be constant on that subinterval. This contradicts the edge equation that its p-flux has derivative -1. Thus the bound is strict on every finite graph when $R < L$. Exact sharpness follows from the brooms constructed next. For $R = L$, the DN interval gives $S_p = L^{q+1}/(q+1)$ by direct integration. □

Proposition 2.3 (Exact brooms and sharp deficit scale)**.** *Join a Dirichlet stem of length $a > 0$ to $n \ge 2$ equal arms of length $b > 0$, with Neumann conditions at their terminal endpoints. Then $L = a + nb$, $R = a + b$, and*

$$S_p = \frac{L^{q+1} - (n^{q+1} - n)b^{q+1}}{q+1}. \tag{10}$$

For every fixed $0 < R < L$, these brooms approach $A_p(L, R)$ while retaining exactly L and R. The stationary deficit exponent $q + 1$ in

$$\frac{L^{q+1}}{q+1} - S_p \ge \frac{(L-R)^{q+1}}{q+1}$$

cannot be replaced by any smaller exponent with a positive uniform coefficient at fixed L.

Proof. With s measured along the stem from its Dirichlet endpoint and t along an arm from the junction, define

$$\begin{aligned} u_{\mathrm{stem}}(s) &= \frac{L^q - (L-s)^q}{q}, \qquad 0 \le s \le a, \\ u_{\mathrm{arm}}(t) &= u_{\mathrm{stem}}(a) + \frac{b^q - (b-t)^q}{q}, \qquad 0 \le t \le b. \end{aligned}$$

Their derivatives have p-fluxes $L - s$ and $b - t$, respectively, since $(q-1)(p-1) = 1$. The forcing equation and endpoint conditions hold. At the junction the sum of outgoing fluxes is $-(L-a) + nb = 0$. Thus these functions solve (5), and uniqueness identifies them with u_p. Equation (6) now gives

$$S_p = \int_0^a (L-s)^q \,\mathrm{d}s + n\int_0^b (b-t)^q \,\mathrm{d}t,$$

which is (10).

For fixed L, R, put $b = (L-R)/(n-1)$ and $a = R - b$, positive for sufficiently large n. Then

$$\frac{L^{q+1}/(q+1) - S_p}{(L-R)^{q+1}} = \frac{n^{q+1} - n}{(q+1)(n-1)^{q+1}} \longrightarrow \frac{1}{q+1}.$$

This proves the asserted exact supremum. For the exponent assertion keep L fixed, take $n = 2$, and let $b \downarrow 0$ with $a = L - 2b$. Here $L - R = b$ and the deficit is exactly $(2^{q+1} - 2)b^{q+1}/(q+1)$. Dividing by any smaller power of b proves the claim. □

Corollary 2.4 (Failure of an inradius-power upper bound)**.** *For each fixed $1 < p < \infty$, there is no finite constant C_p such that*

$$S_p(G, D) \le C_p L R^q$$

for every graph in this class. Equivalently, there is no universal bound $\mathcal{T}_p(G, D) \le C_p L^{p-1} R^p$ in the powered convention. The leading small-inradius scale $L^q R$ has optimal coefficient one.

Proof. For integers $k \ge 2$, take

$$n = k^2, \qquad a = \frac{1}{k+1}, \qquad b = \frac{1}{k(k+1)}.$$

These are finite brooms with $L = 1$ and $R = 1/k$. Their exact value is

$$S_p = \frac{1}{q+1}\left[1 - \left(\frac{k}{k+1}\right)^{q+1} + \frac{k^{1-q}}{(k+1)^{q+1}}\right].$$

For fixed $q > 1$, differentiability of $(1-t)^{q+1}$ at zero gives $kS_p \to 1$; the final term is $O(k^{-2q}) = o(k^{-1})$. Consequently $S_p/R^q \sim k^{q-1} \to \infty$, whereas $S_p/R \to 1$. Raising to $p-1$ proves the powered statement, because $(q-1)(p-1) = 1$. Finally (9) implies $S_p \le L^q R$, and the same sequence proves the optimal leading coefficient. □

For $p = 2$ the failed form is $T \le CLR^2$. A particular constant-four analogy with Makai's domain inequality was raised in [4, Remark 4.7(1)]. The negative example has classical network ancestry: the explicit stower formula in [4, Example 3.10], with many small loop petals on one Dirichlet stem, also yields $T \asymp R$ at fixed length as $R \downarrow 0$. The broom calculation above gives the elementary Neumann-arm version. The sharp fixed-(L, R) envelope, rather than the computation of torsion on a star or stower, is the joint geometric comparison established here. All statements concern a fixed exponent $1 < p < \infty$.

3 The sharp positive-resolvent envelope

Return to the linear operator $H = -\,\mathrm{d}^2/\,\mathrm{d}x^2$ with Dirichlet conditions on D and standard continuity/Kirchhoff conditions elsewhere. For $z > 0$, write

$$J_G(z) = \langle \mathbf{1}, (H+z)^{-1}\mathbf{1}\rangle, \qquad s = \sqrt{z},$$

and define

$$F_{L,R}(z) = \frac{L}{z} - \frac{\tanh(sR) + s(L-R)}{z^{3/2}\big[1 + s(L-R)\tanh(sR)\big]}. \tag{11}$$

The following is a resolvent comparison; the pointwise heat comparison with the endpoint-mass model is proved for rooted trees in Section 7.

Theorem 3.1. *For every $z > 0$,*

$$J_G(z) \le F_{L,R}(z).$$

For each prescribed $0 < R < L$ and $z > 0$, this is the exact supremum over finite graphs with those L, R. The DN interval attains the endpoint $F_{L,L}(z) = L/z - \tanh(sL)/z^{3/2}$.

Proof. The anchored form is coercive, and its resolvent solution $u = (H + z)^{-1}\mathbf{1}$ satisfies

$$\int_G u'f' \, \mathrm{d}x + z\int_G uf \, \mathrm{d}x = \int_G f \, \mathrm{d}x \qquad (f \in V_2(G, D)).$$

Testing with the negative part gives $u \ge 0$. Testing with $(u - 1/z)_+$, which vanishes on D, gives

$$\int_G |((u - 1/z)_+)'|^2 \, \mathrm{d}x + z\int_G (u - 1/z)_+^2 \, \mathrm{d}x = 0.$$

Hence $0 \le u \le 1/z$. Testing by u and completing the form square also gives

$$J_G(z) = \sup_{f \in V_2(G,D)} \left\{ 2\int_G f \, \mathrm{d}x - \int_G |f'|^2 \, \mathrm{d}x - z\int_G f^2 \, \mathrm{d}x \right\}. \tag{12}$$

The supremum is attained by u.

Choose a maximum point of u, and a shortest anchored path to it of length $r \le R$. Set $g = u$ along that path, parameterized from its Dirichlet endpoint. On $[0, 1/z]$, the function $w(v) = 2v - zv^2$ is nondecreasing. Thus the complement contribution is at most $(L-r)w(g(r))$; discarding only its nonnegative gradient energy yields

$$J_G(z) \le \int_0^r (2g - zg^2 - |g'|^2) \, \mathrm{d}y + (L - r)\big[2g(r) - zg(r)^2\big]. \tag{13}$$

We may bound this by the supremum over all real $g \in H^1(0, r)$ with $g(0) = 0$. This strictly concave functional has the unique maximizer v satisfying, with $\beta_r = L - r$,

$$-v'' + zv = 1, \qquad v(0) = 0, \qquad v'(r) = \beta_r\big(1 - zv(r)\big).$$

The boundary condition follows by integration by parts at the free endpoint; when $\beta_r = 0$ it is Neumann. Put $t = \tanh(sr)$ and $b = s\beta_r$. Direct solution gives

$$v(y) = \frac{1 - \cosh(sy) + A\sinh(sy)}{z}, \qquad A = \frac{t + b}{1 + bt}. \tag{14}$$

All denominators are positive. Integration of its equation and the endpoint condition gives

$$z\left[\int_0^r v \, \mathrm{d}y + \beta_r v(r)\right] + v'(0) = L.$$

Testing the endpoint-mass weak equation by v shows that the maximum of (13) is $\int_0^r v \, \mathrm{d}y + \beta_r v(r)$. Since $v'(0) = A/s$, this maximum is $F_{L,r}(z)$.

It remains to vary r while keeping the total length L fixed. Put $x = sr$, $\ell = sL$, $b = \ell - x$ and $t = \tanh x$. Differentiation gives

$$\frac{\mathrm{d}}{\mathrm{d}x}\frac{t + b}{1 + bt} = -\frac{b^2(1 - t^2)}{(1 + bt)^2}.$$

Therefore $F_{L,r}(z)$ is nondecreasing in r, and $J_G(z) \le F_{L,r}(z) \le F_{L,R}(z)$. This does not assume that the resolvent maximum occurs at a point realizing the inradius.

For sharpness, use a broom with stem a and n equal arms b. An arm with junction value c has the solution

$$u_{\mathrm{arm}}(t) = \frac{1}{z} + \left(c - \frac{1}{z}\right) \frac{\cosh(s(b-t))}{\cosh(sb)}.$$

Its outgoing derivative at the junction is $(1-zc)\tanh(sb)/s$. Kirchhoff gives the stem condition $u'_{\mathrm{stem}}(a) = n\tanh(sb)(1 - zu(a))/s$. Solving the stem as in (14) yields

$$u'_{\mathrm{stem}}(0) = \frac{A_n}{s}, \qquad A_n = \frac{\tanh(sa) + n\tanh(sb)}{1 + n\tanh(sb)\tanh(sa)}.$$

Integration of the graph equation cancels all non-Dirichlet fluxes and gives $u'_{\mathrm{stem}}(0)+zJ_G(z) = L$. Hence its exact resolvent is

$$J_G(z) = \frac{L}{z} - \frac{A_n}{z^{3/2}}. \tag{15}$$

At fixed $0 < R < L$, take $b = (L-R)/(n-1)$ and $a = R - b > 0$. Then $a \to R$ and $n\tanh(sb) \to s(L-R)$, proving convergence to (11). Every finite graph in the sequence has exactly the prescribed L, R. At $R = L$, direct solution on the DN interval gives the stated endpoint value. □

Corollary 3.2 (An explicit weighted heat deficit)**.** *Let I_L be the length-L DN interval. Then, for $z > 0$,*

$$\begin{aligned} J_{I_L}(z) - J_G(z) &\geq J_{I_L}(z) - F_{L,R}(z) \\ &= \int_R^L \frac{(L-r)^2\operatorname{sech}^2(sr)}{[1 + s(L-r)\tanh(sr)]^2}\,\mathrm{d}r \qquad (16) \\ &\geq \frac{\operatorname{sech}^2(sL)}{3(1+sL)^2}(L-R)^3. \qquad (17) \end{aligned}$$

The middle expression is the sharp envelope deficit. It is positive for $R < L$ and tends to $(L-R)^3/3$ as $z \downarrow 0$.

Proof. The derivative computed above gives exactly

$$\frac{\partial F_{L,r}(z)}{\partial r} = \frac{(L-r)^2\operatorname{sech}^2(sr)}{[1 + s(L-r)\tanh(sr)]^2}.$$

Integrating from R to L proves (16). On this interval the numerator's hyperbolic factor is at least $\operatorname{sech}^2(sL)$, while the denominator is at most $(1+sL)^2$. Integration of $(L-r)^2$ proves (17). As $z \downarrow 0$, the integrand tends to $(L-r)^2$ and is bounded by it. Dominated convergence proves the limit. Also $J_{I_L}(z) \to L^3/3$, so the stationary $p = 2$ envelope is recovered without requiring cancellation of divergent terms as a proof step. □

If $\mathcal{Q}_G(t)$ denotes the heat content for generator $-H$, the spectral semigroup–resolvent identity gives

$$J_G(z) = \int_0^\infty e^{-zt}\mathcal{Q}_G(t)\,\mathrm{d}t.$$

Thus (16) is an exponentially weighted all-time heat-content deficit bound. Pointwise heat ordering against the endpoint-mass model is obtained on rooted trees and exact tree quotients by the positive-kernel arguments of Section 7, and fixed-time stability rates on every graph by the parabolic argument of Section 8. The stationary and resolvent proofs use classical variational duality, the maximum principle and elementary interval equations.

4 Marked measured geometry

Throughout this section normalize total length to one. Distances are rescaled by L^{-1} and arclength measure by L^{-1} when starting from a graph of length L. Write

$$R = \max_{x \in G} \operatorname{dist}(x, D), \qquad \beta = 1 - R.$$

The interval used for geometric comparison is $[0, 1]$ marked at its Dirichlet endpoint 0. Reflection identifies its heat content with that of the physical interval in Section 5.

Definition 4.1. Let $d_m(G, I)$ be the infimum over common isometric embeddings of the maximum of the Hausdorff distance between the supports, the Hausdorff distance between their closed Dirichlet marked sets, and the Prokhorov distance between their arclength probability measures. The Prokhorov distance is the infimum of $\varepsilon > 0$ such that $\mu(A) \le \nu(A^\varepsilon) + \varepsilon$ and $\nu(A) \le \mu(A^\varepsilon) + \varepsilon$ for every Borel set A; A^ε denotes its open ε-neighborhood.

Theorem 4.2 (Geometric consequence of the inradius reserve)**.** *For every graph in the stated model,*

$$d_m(G, I) \le 2\beta.$$

Consequently, for every fixed $1 < p < \infty$, $q = p/(p-1)$, and every original length L,

$$d_m(G/L, I) \le 2 \left[\frac{L^{q+1} - (q+1) S_p(G)}{L^{q+1}} \right]^{1/(q+1)}. \tag{18}$$

The exponent $1/(q+1)$ cannot be increased in an estimate uniform over these graphs, even with a fixed graph topology.

Proof. Choose x_* at distance R from D and a shortest path γ from a closest $d_0 \in D$ to x_*. This path is an isometric interval: a shortcut between two of its points would shorten the whole path. Its complement has total length β. Every off-path point connects to its first attachment on γ by a simple path of length at most β. The same statement applies to another Dirichlet vertex d. If its first attachment is $\gamma(s)$ and that connecting path has length $\ell \le \beta$, then

$$R \le \operatorname{dist}(x_*, d) \le R - s + \ell.$$

Thus $s \le \ell$ and $\operatorname{dist}(d, d_0) \le 2\beta$. A Dirichlet vertex already on γ must be d_0, by the same inequality with $\ell = 0$.

Attach a new dead-end segment of length β at x_*. In the resulting space both G and the interval formed by γ followed by this segment embed isometrically. Their support Hausdorff distance is at most β and their marked-set Hausdorff distance is at most 2β. Their measures agree on γ, of mass $1-\beta$, and the remaining mass is β for each. Their total-variation distance, and hence their Prokhorov distance, is at most β. This proves the embedding bound. The stationary reserve gives $\beta^{q+1} \le [L^{q+1} - (q+1)S_p(G)]/L^{q+1}$, proving (18).

For the exponent, take a length-one broom with three equal arms of length b and a stem of length $1 - 3b$, where $0 < b < 1/4$. Its diameter is $1 - 2b$, so its ordinary Gromov–Hausdorff distance from the unit interval is at least b: any common embedding has Hausdorff distance at least half the difference of diameters. Its exact torsion deficit is

$$\frac{1}{q+1} - S_p = \frac{3^{q+1} - 3}{q+1} b^{q+1}.$$

Since d_m dominates the ordinary Gromov–Hausdorff distance, no larger deficit exponent can hold uniformly as $b \downarrow 0$. □

5 The constant-data heat deficit and its positive source

Relation to the companion paper. This section overlaps with [A]. The all-times inequality $\mathcal{Q}_G \le \mathcal{Q}_{I_L}$ is [A, Theorem 1.2], where it follows from a concentration comparison for arbitrary nonnegative L^2 data [A, Theorem 1.1]. Lemma 5.1, Lemma 5.2, Theorem 5.3 and Corollary 5.4 correspond to [A, Lemma 4.1, Lemma 3.2, Theorem 4.2 and Corollary 4.5]. Only initial datum one is needed here, and the argument below obtains $W \ge 0$ directly from the source representation. The section is therefore self-contained, and its quantitative source identities are the ones used in Sections 6 and 8.

Let G be a finite compact connected metric graph obtained by identifying endpoints of finitely many intervals of positive lengths ℓ_e. Its total length is $L = \sum_e \ell_e > 0$, and integration uses arclength; vertices have measure zero. Loops and multiple edges are allowed, and a loop contributes two germs at its vertex. Let D be a nonempty set of vertices. The form

$$a_G(f,g) = \sum_e \int_e f'\overline{g'}\,\mathrm{d}x, \qquad V = \{f \in H^1(G) : f|_D = 0\},$$

where $H^1(G)$ means continuous and edgewise H^1, defines the self-adjoint operator H_G. It acts as $-d^2/dx^2$, with continuity and unweighted Kirchhoff conditions outside D. There is no additional flux condition at a Dirichlet vertex. A non-Dirichlet leaf is Neumann. The heat generator is $+d^2/dx^2$, without a factor $1/2$.

The Dirichlet anchor gives a useful elementary coercivity estimate. A simple path from D to any $x \in G$ has length at most L, so

$$|f(x)| \le \sqrt{L}\,\|f'\|_{L^2(G)}, \qquad \|f\|^2_{L^2(G)} \le L^2 a_G(f,f) \quad (f \in V).$$

Thus H_G has a positive spectral gap. The finite-edge Sobolev embedding also makes its resolvent compact. Inserting or suppressing a non-Dirichlet vertex of degree two changes neither this form nor its heat semigroup.

Cutting every Dirichlet incidence separates the form into finitely many positive-length components, each anchored at a Dirichlet endpoint. A path from any point to D proves that each component is anchored. In particular $G \setminus D$ need not be connected. The semigroup $T_G(t) = e^{-tH_G}$ is positive and sub-Markovian, by the usual form contraction property. On each cut component it is positivity improving. Here one can use the classical strong parabolic maximum principle on the open edges: an interior zero at a positive time forces vanishing backwards on that edge. At a zero non-Dirichlet vertex all outgoing derivatives are nonnegative. If an adjacent edge solution is positive, the boundary Hopf lemma makes its outgoing derivative strictly positive, contradicting the Kirchhoff sum. Vanishing therefore propagates through the connected component. A nonzero initial datum cannot have a zero evolved component, since the spectral multipliers $e^{-t\lambda}$ are nonzero. This proves strict positivity off the Dirichlet endpoints for any nonzero nonnegative component datum. This is the standard positivity mechanism for these graph forms; see also [9, Theorem A.2].

Only the initial datum $\mathbf{1}$ is used in this section. Write

$$u(t) = T_G(t)\mathbf{1}, \qquad \mathcal{Q}_G(t) = \langle \mathbf{1}, T_G(t)\mathbf{1}\rangle.$$

Thus $\mathcal{Q}_G$ is heat content, not heat trace. Let $I_L = [0,L]$ have Neumann condition at 0 and Dirichlet condition at L, and write $v(t) = T_{I_L}(t)\mathbf{1}$. Its explicit heat content is

$$\mathcal{Q}_{I_L}(t) = \frac{8L}{\pi^2} \sum_{n\ge 0} \frac{e^{-(2n+1)^2\pi^2 t/(4L^2)}}{(2n+1)^2}. \tag{19}$$

Its torsion solution is $(L^2 - x^2)/2$, and consequently

$$\int_0^\infty \mathcal{Q}_{I_L}(t)\,\mathrm{d}t = \frac{L^3}{3}. \tag{20}$$

Reflection gives the same heat content when the Dirichlet mark is placed at 0 for later geometric comparisons.

5.1 Level coordinates for the survival solution

For a nonnegative function f on the graph, define its top-mass profile by

$$\mathcal{M}f(s) = \sup_{|E|=s} \int_E f\,\mathrm{d}x = \int_0^s f^*(y)\,\mathrm{d}y, \qquad 0 \le s \le L,$$

where f^* is its decreasing rearrangement. The supremum allows measurable parts of a level set. Directly from this formula,

$$\|\mathcal{M}f - \mathcal{M}g\|_\infty \le \|f - g\|_1 \le \sqrt{L}\,\|f - g\|_2 \qquad (f, g \ge 0). \tag{21}$$

Set

$$U(t,s) = \mathcal{M}u(t)(s), \qquad F(t,s) = \int_0^s v(t,x)\,\mathrm{d}x, \qquad W = F - U.$$

No sign of W is assumed at this point.

Lemma 5.1 (Positive-time survival profiles)**.** *For every $t > 0$, $u(t) > 0$ off D and $u_{xx}(t,x) = u_t(t,x) < 0$ on the open edges. Each edge profile is strictly concave and has at most one interior critical point. All edge derivatives needed below are bounded locally uniformly for positive time.*

Proof. Positivity and sub-Markovianity give

$$u(t+h) = T_G(t)T_G(h)\mathbf{1} \le T_G(t)\mathbf{1} = u(t).$$

Spectral calculus puts $u(t)$ in every power domain of H_G for $t > 0$; the edge equation and one-dimensional Sobolev regularity give smooth edgewise representatives and locally uniform derivative bounds. Therefore $w(t) = -u_t(t) = H_G u(t) \ge 0$. On each anchored cut component, $u(r)$ is nonzero by injectivity and the initial component datum $\mathbf{1}$. If $w(r) = 0$ on that component, its trivial operator kernel would give $u(r) = 0$, a contradiction. For $0 < r < t$, $w(t) = T_G(t-r)w(r)$, so positivity improvement gives $w(t) > 0$ on every open edge and at non-Dirichlet vertices. The edge heat equation yields $u_{xx} = u_t = -w < 0$. Positivity of u follows from the same component positivity argument applied directly to $u(t)$. Strict decrease of its edge derivative proves the critical-point assertion. □

At each positive time there are therefore only finitely many vertex and critical levels, and every level set has length zero. The coarea argument below is the graph rearrangement mechanism of [3, Lemma 3]; the integrated parabolic formulation has classical symmetrization ancestry [7, 8]. We print the needed constant-data argument.

Lemma 5.2 (Inverse-distribution regularity)**.** *For each $t > 0$, the decreasing rearrangement $q(t,\cdot) = u(t)^*$ extends by $q(t,0) = \max u(t)$ and $q(t,L) = 0$ to a Lipschitz function. Consequently $U(t,\cdot) \in W^{2,\infty}(0,L)$, with $U(t,0) = 0$ and $U_s(t,L) = 0$, locally uniformly for positive times.*

Proof. Fix a time, let $M = \max_e \|u_e'\|_\infty > 0$, and set $\mu(z) = |\{u > z\}|$. A simple arclength path from a point of D to a maximizer crosses every level between zero and $\max u$. For $0 \le \alpha < \beta \le \max u$, choose the first β crossing on that path and the last preceding α crossing. The intervening open segment has $\alpha < u < \beta$, is counted only once in edge measure, and has length at least $(\beta - \alpha)/M$. Hence

$$\mu(\alpha) - \mu(\beta) \ge (\beta - \alpha)/M.$$

The distribution is continuous because all level sets have zero length; it strictly decreases from L to zero. Its inverse is therefore M-Lipschitz, including the endpoint extensions. Integrating that inverse gives the asserted spatial regularity. The derivative bounds from Lemma 5.1 are uniform on compact positive-time intervals. No connectedness of the Dirichlet-cut interior was used. □

For a regular level z of a positive-time profile, let $s = \mu(z)$ and sum over all its crossings:

$$A = \sum_{u=z} |u_x|, \qquad B = \sum_{u=z} |u_x|^{-1}, \qquad N = \#\{u = z\}.$$

The path in Lemma 5.2 ensures $N \ge 1$. Coarea on the finitely many monotone edge pieces and inverse differentiation give

$$-\mu'(z) = B, \qquad U_{ss}(t,s) = -1/B, \qquad AB \ge N^2 \ge 1. \tag{22}$$

The top-s set is the hot set $E(t,s) = \{u(t) > q(t,s)\}$, up to null sets. Its envelope derivative is

$$U_t(t,s) = \int_{E(t,s)} u_t(t,x)\,\mathrm{d}x = -A. \tag{23}$$

To justify the first equality, bracket the time difference with the old and new maximizing sets. Uniform convergence of u and continuity of its inverse distribution place their symmetric difference in a shrinking band around a null level set. The two difference quotients have the same limit. For the second equality integrate $u_t = u_{xx}$ over the hot set. Every hot non-Dirichlet vertex includes all its germs and its flux cancels by Kirchhoff. Dirichlet vertices do not occur at a positive hot level. Each boundary crossing contributes $-|u_x|$. Disconnected hot sets give the same cancellation. Also $|U(t,s) - U(r,s)| \le \|u(t) - u(r)\|_1$ gives local Lipschitz regularity in time, uniformly in s.

5.2 The positive heat-deficit source

On the mass interval $[0, L]$ let

$$\mathsf{A} = -d^2/ds^2, \qquad f(0) = 0, \quad f'(L) = 0, \qquad \mathcal{S}(t) = e^{-t\mathsf{A}},$$

and let $K(t; s, y)$ be its kernel. This semigroup is positive and an L^∞ contraction by the mixed maximum principle. Its positive-time kernel is smooth and

$$K(t; s, y) = K_{DD,2L}(t; s, y) + K_{DD,2L}(t; s, 2L - y) > 0 \quad (t > 0,\ s, y \in (0, L]),$$

by reflection at L, where $K_{DD,2L}$ is the usual Dirichlet kernel on $(0, 2L)$. Its Green kernel is

$$\int_0^\infty K(h; s, y)\,\mathrm{d}h = \min(s, y), \tag{24}$$

as follows by solving the mixed one-dimensional inverse problem. At the Dirichlet mass endpoint, the inward boundary derivative is strictly positive by the parabolic Hopf lemma. Thus $K(h; L, y)/y$ has a positive continuous extension at $y = 0$, uniformly for h in any compact positive window. These facts concern this fixed interval, not heat kernels on a varying graph.

Theorem 5.3 (Exact constant-data source)**.** *There is a jointly measurable nonnegative function $d(t,s)$, bounded on compact positive-time cylinders, such that at almost every mass coordinate of every positive-time profile,*

$$d = A - \frac{1}{B} = \frac{N^2-1}{B} + \frac{1}{B}\sum_{i<j}\frac{(\alpha_i-\alpha_j)^2}{\alpha_i\alpha_j}, \qquad \alpha_i = |u_x| \text{ at the crossings.} \tag{25}$$

The deficit satisfies

$$W_t - W_{ss} = d, \qquad W(t,0) = 0, \quad W_s(t,L) = 0,$$

and, for every $t > 0$ and $0 \le s \le L$,

$$W(t,s) = \int_0^t \int_0^L K(t-r;s,y)d(r,y)\,\mathrm{d}y\,\mathrm{d}r. \tag{26}$$

The integral is the finite increasing limit from source times $r \ge \varepsilon$ as $\varepsilon \downarrow 0$. In particular $W \ge 0$, so $\mathcal{Q}_G(t) \le \mathcal{Q}_{I_L}(t)$ for all $t \ge 0$, which is [A, Theorem 1.2].

Proof. Equations (22)–(23) give $U_t - U_{ss} = -(A - 1/B)$. Direct expansion gives

$$AB - N^2 = \sum_{i<j}\left(\frac{\alpha_i}{\alpha_j} + \frac{\alpha_j}{\alpha_i} - 2\right),$$

proving (25) and nonnegativity. Every regular level has at most two crossings per edge. If $M(t) = \max_e \|u_x(t)\|_\infty$, then $0 \le d \le A \le 2|\mathsf{E}(G)|M(t)$. The weak time and spatial derivatives define a jointly measurable version. At each fixed time there are finitely many exceptional mass coordinates. The established Sobolev and local Lipschitz bounds exclude any singular residual in the space-time equation.

For the physical interval, Lemma 5.1 gives $v_{xx} < 0$ at positive times, while its reflecting condition is $v_x(t,0) = 0$. Thus v is decreasing from that endpoint. Integrating its heat equation gives $F_t = F_{ss}$, with $F(t,0) = 0$ and $F_s(t,L) = v(t,L) = 0$.

Fix $0 < \varepsilon < t$. Variation of constants for the weak mixed heat problem on $[\varepsilon, t]$ yields

$$\begin{aligned} W(t,s) = {} & (\mathcal{S}(t-\varepsilon)W(\varepsilon,\cdot))(s) \\ & + \int_\varepsilon^t \int_0^L K(t-r;s,y)d(r,y)\,\mathrm{d}y\,\mathrm{d}r. \end{aligned} \tag{27}$$

The identity first holds in L^2; the continuous initial profiles and positive-time kernel smoothing make the initial term continuous. For the source integral, split off a short final-time strip: its sup norm is bounded by the strip length times the local L^∞ source bound, while on the remaining strip the kernel is smooth. This gives a continuous representative and equality for every s, including L.

Strong L^2 continuity of both heat semigroups and (21) imply $U(\varepsilon,\cdot) \to s$ and $F(\varepsilon,\cdot) \to s$ uniformly. Hence $\|W(\varepsilon,\cdot)\|_\infty \to 0$. The contraction property gives

$$\|\mathcal{S}(t-\varepsilon)W(\varepsilon,\cdot)\|_\infty \le \|W(\varepsilon,\cdot)\|_\infty \longrightarrow 0.$$

No sign of this initial term is required. The source integral in (27) is nonnegative and increases as ε decreases. That same identity bounds it by $|W(t,s)| + \|W(\varepsilon,\cdot)\|_\infty$, so its limit is finite and equals $W(t,s)$. This proves (26), and derives $W \ge 0$ rather than assuming a previous concentration theorem. At $t = 0$ both heat contents equal L. □

Corollary 5.4 (Integrated constant-data source)**.** *For $0 \le s \le L$,*

$$\int_0^\infty W(t,s)\,\mathrm{d}t = \int_0^\infty \int_0^L \min(s,y) d(r,y)\,\mathrm{d}y\,\mathrm{d}r.$$

In particular

$$\frac{L^3}{3} - \langle \mathbf{1}, H_G^{-1}\mathbf{1}\rangle = \int_0^\infty \int_0^L y\, d(r,y)\,\mathrm{d}y\,\mathrm{d}r. \tag{28}$$

For $L = 1$, $0 \le \Delta_G(t) = \mathcal{Q}_{I_1}(t) - \mathcal{Q}_G(t) \le \mathcal{Q}_{I_1}(t)$ and $\int_0^\infty \mathcal{Q}_{I_1}(t)\,\mathrm{d}t = 1/3$.

Proof. Tonelli in (26) and (24) gives the identity. Its left side is finite because $0 \le W(t,s) \le F(t,s) \le \mathcal{Q}_{I_L}(t)$ and (20) holds. At $s = L$, integrate both heat contents; spectral calculus and coercivity give $\int_0^\infty \mathcal{Q}_G(t)\,\mathrm{d}t = \langle \mathbf{1}, H_G^{-1}\mathbf{1}\rangle$. □

6 A backward integral estimate

In this section normalize total length to one and write $I = I_1$. Put $\Delta_G(t) = \mathcal{Q}_I(t) - \mathcal{Q}_G(t)$. For datum one, Theorem 5.3 gives

$$\Delta_G(t) = \int_0^t \int_0^1 K(t-r;1,y) d(r,y)\,\mathrm{d}y\,\mathrm{d}r, \qquad d \ge 0. \tag{29}$$

This is the fixed mixed kernel in the mass coordinate, not the graph kernel. Its Green integral is

$$\int_0^\infty K(h;1,y)\,\mathrm{d}h = y.$$

For $0 < a \le b < \infty$ define

$$c(a,b) = \min_{\substack{a\le h\le b\\ 0\le y\le 1}} \frac{K(h;1,y)}{y} > 0, \tag{30}$$

where the quotient at $y = 0$ is the inward derivative. To justify positivity, positive-time smoothness and positivity of this fixed interval kernel give positivity for $y > 0$, including its Neumann endpoint. Reflection across the Neumann endpoint reduces the Dirichlet endpoint to the ordinary interval kernel; the parabolic boundary Hopf lemma gives a strictly positive inward derivative. The quotient therefore extends continuously and positively on the displayed compact set. These facts involve only a fixed interval.

Lemma 6.1 (Early integrated deficit from one observation)**.** *Fix $0 < \tau_0 \le \tau_1 < \infty$, set $T = \tau_0/2$ and $c = c(\tau_0/2, \tau_1)$. For every $t_0 \in [\tau_0, \tau_1]$,*

$$\int_0^T \Delta_G(t)\,\mathrm{d}t \le \frac{\Delta_G(t_0)}{c}. \tag{31}$$

Proof. Tonelli and the Green integral give

$$\int_0^T \Delta_G(t)\,\mathrm{d}t \le \int_0^T \int_0^1 y\, d(r,y)\,\mathrm{d}y\,\mathrm{d}r.$$

In (29) at t_0, retain $r \le T$. Then $t_0 - r \in [\tau_0/2, \tau_1]$, and the retained integral is at least c times the right side. All integrands are nonnegative; the monotone interpretation at initial time from Theorem 5.3 makes both Tonelli steps valid without a separate initial integrability assumption. □

7 The sharp heat envelope on rooted trees

We now retain the endpoint mass as a positive heat model. For $r > 0$ and $\beta \geq 0$, let $E(r, \beta)$ have speed measure $\mu_{r,\beta} = \mathrm{d}x + \beta\delta_r$ on $[0, r]$ and quadratic form

$$\mathcal{E}(f, g) = \int_0^r f'\overline{g'}\ \mathrm{d}x, \qquad f, g \in H^1(0, r), \quad f(0) = g(0) = 0.$$

Its total mass is $r + \beta$. At $\beta = 0$ it is the ordinary DN interval. For $\beta > 0$ the heat equation is $u_t = u_{xx}$ in the interior, with $\beta u_t(t, r) = -u_x(t, r)$ at the endpoint. Write $Q_{r,\beta}(t) = \langle \mathbf{1}, e^{-tH_{r,\beta}}\mathbf{1}\rangle_{\mu_{r,\beta}}$. The initial datum and this integral both include the endpoint atom. The resolvent calculation in Section 3 gives

$$\widehat{Q}_{r,\beta}(z) = F_{r+\beta,r}(z),$$

where F is defined by (11).

7.1 A positive model variation

Lemma 7.1 (Endpoint absorption densities)**.** *For every $r > 0$ and $\beta \geq 0$ there is a continuous strictly positive probability density $k_{r,\beta}$ on $(0, \infty)$ with transform*

$$h_{r,\beta}(z) = \frac{1}{\cosh(r\sqrt{z}) + \beta\sqrt{z}\sinh(r\sqrt{z})}. \tag{32}$$

The densities and their self-convolutions are jointly continuous for r in a compact positive interval, β in a compact nonnegative interval, and time in a compact subinterval of $(0, \infty)$.

Proof. The form is dense, closed and Markovian. For $\beta > 0$, thin boundary layers approximate the endpoint coordinate independently in $L^2(\mu)$; thus the trace constraint in the form domain does not prevent density. The bounds $|f(r)|^2 \leq r\mathcal{E}(f, f)$ and $\int |f|^2 \leq r^2\mathcal{E}(f, f)$ give coercivity. Compactness of the H^1 embedding, including its endpoint trace, gives compact resolvent and strictly positive spectral bottom.

Put $v(t) = e^{-tH}\mathbf{1}$. The Markov property gives $0 \leq v \leq 1$ and $v(t + s) \leq v(t)$. For positive time, $g(t) = -v_t(t) = He^{-tH}\mathbf{1}$ is nonnegative and nonzero. Interior positivity follows from the strong maximum principle applied to $g(t) = e^{-tH/2}g(t/2)$. It holds at r as well. Indeed, if a nonnegative positive-time solution vanished at r, its time derivative there would vanish, whereas the boundary Hopf lemma would give a strictly negative outward derivative. This contradicts $\beta g_t(r) = -g_x(r)$, or the Neumann condition when $\beta = 0$. Positive-time smoothing gives the continuous traces used here. Thus $k_{r,\beta}(t) = g(t, r) > 0$. For $\beta > 0$, strong initial $L^2(\mu)$ continuity gives $v(0+, r) = 1$; at $\beta = 0$ the ordinary DN kernel gives the same limit. Coercivity and smoothing give $v(\infty, r) = 0$, so $\int k_{r,\beta} = 1$.

For $u = (H + z)^{-1}\mathbf{1}$, integration by parts in time gives $\widehat{k}(z) = 1 - zu(r)$. The function $a = 1 - zu$ solves

$$a'' = za, \qquad a(0) = 1, \qquad a'(r) = -\beta z a(r).$$

Its endpoint value is (32). To check parameter continuity, take $z = \sigma + i\omega$, $\sigma > 0$, and the square root w with positive real part. For $p(x) = \cosh(wx)/\cosh(wr)$, integration of $p'' = zp$ gives

$$w\tanh(rw) = \int_0^r |p'|^2\ \mathrm{d}x + z\int_0^r |p|^2\ \mathrm{d}x.$$

Its real part is nonnegative. Hence $|1 + \beta w\tanh(rw)| \geq 1$ and $|h_{r,\beta}(z)| \leq |\operatorname{sech}(rw)|$. For $r \geq a > 0$,

$$|\operatorname{sech}(rw)| \leq \frac{2e^{-r\operatorname{Re} w}}{1 - e^{-2a\sqrt{\sigma}}}.$$

Since $\operatorname{Re}\sqrt{\sigma+i\omega}$ grows like $\sqrt{|\omega|/2}$, this is an integrable vertical-line majorant for both h and h^2, uniformly over the stated parameters. Absolute Bromwich inversion gives the asserted joint continuity, including $\beta = 0$. Tonelli and transform uniqueness identify the inverse of h^2 with $k * k$. □

Proposition 7.2 (Positive radius variation)**.** *For fixed $L > 0$, $0 < R < L$ and $t > 0$,*

$$\mathcal{Q}_{I_L}(t) - Q_{R,L-R}(t) = \int_R^L (L-r)^2 (k_{r,L-r} * k_{r,L-r})(t)\ \mathrm{d}r. \tag{33}$$

For each window $0 < \tau_0 \le \tau_1 < \infty$ there is $c > 0$ such that, at unit total mass,

$$\mathcal{Q}_{I_1}(\tau) - Q_{R,1-R}(\tau) \ge \frac{c}{24}(1-R)^3 \qquad (0 < R < 1,\ \tau \in [\tau_0, \tau_1]). \tag{34}$$

Proof. The derivative in the proof of Corollary 3.2 is

$$\partial_r F_{L,r}(z) = (L-r)^2 h_{r,L-r}(z)^2.$$

Integrate from R to L. Lemma 7.1 supplies the positive inverse convolution for every integrand. Tonelli and transform uniqueness prove (33); continuity upgrades the identity to every positive time. This uses an identified positive inverse, rather than an implication from scalar transform order. At $L = 1$ put

$$c = \min_{\substack{1/2 \le r \le 1 \\ \tau_0 \le \tau \le \tau_1}} (k_{r,1-r} * k_{r,1-r})(\tau) > 0.$$

Positivity, continuity and compactness give the strict inequality. Restrict (33) to $r \in [(1+R)/2, 1]$. The remaining weight integral is $(1-R)^3/24$. □

7.2 Positive rooted responses and parallel merging

For a finite singly rooted graph, or a rooted interval model with endpoint mass, let τ_x be absorption time and $v_z(x) = \mathbb{E}_x e^{-z\tau_x}$. For real $z > 0$, it solves $v_z'' = z v_z$, has value one at the root and natural conditions elsewhere. Let $p(z)$ be the negative sum of its outward root derivatives, and let M be its total speed mass. Integrating the equation cancels the other vertex fluxes, including the dynamic endpoint contribution, and gives

$$p(z) = z \int v_z\ \mathrm{d}\mu, \qquad J(z) = \frac{M}{z} - \frac{p(z)}{z^2}. \tag{35}$$

If $U(t)$ is the absorption CDF with initial distribution μ/M, then

$$\frac{p(z)}{z^2} = M \int_0^\infty e^{-zt} U(t)\ \mathrm{d}t.$$

For $E(r, \beta)$, direct solution gives, with $k = \sqrt{z}$,

$$p_{r,\beta}(z) = k \frac{\tanh(kr) + k\beta}{1 + k\beta \tanh(kr)}. \tag{36}$$

Its endpoint-start absorption law has transform $h_{r,\beta}$.

We will use a pathwise monotonicity of those endpoint laws. Let B be standard Brownian motion and set

$$Y_u = \sqrt{2} B_u + \Lambda_u, \qquad \Lambda_u = \max\{0, -\inf_{0 \le v \le u} \sqrt{2} B_v\}, \qquad \sigma_r = \inf\{u : Y_u = r\}.$$

The boundary regulator Λ is normalized for generator d^2/dx^2. The time

$$T_{r,\beta} = \sigma_r + \beta\Lambda_{\sigma_r} \tag{37}$$

has transform $h_{r,\beta}$. To verify the coefficient of the clock, apply Itô's formula to $e^{-z(u+\beta\Lambda_u)}f(Y_u)$, stopped at σ_r. The interior drift is $(f'' - zf)\,\mathrm{d}u$ and its boundary drift is $[f'(0) - z\beta f(0)]\,\mathrm{d}\Lambda_u$. Take

$$f(r) = 1, \qquad f'' = zf, \qquad f'(0) = z\beta f(0).$$

The resulting expectation is (32), which also fixes the endpoint local-time convention. On the same path, both σ_r and Λ_{σ_r} increase with r. Therefore

$$r \le R, \quad \gamma \le \eta \quad \Longrightarrow \quad T_{r,\gamma} \le T_{R,\eta} \quad \text{on this coupling.} \tag{38}$$

Absorption from any starting point of $E(r,\gamma)$ is stochastically no larger than absorption from its far endpoint: the endpoint-start path must first hit that point, after which the strong Markov property supplies its remaining absorption time. Averaging includes the atom and gives

$$\tau_{\mathrm{unif},r,\gamma} \le_{\mathrm{st}} T_{r,\gamma}, \qquad \text{initial law } \frac{\mathrm{d}x + \gamma\delta_r}{r+\gamma}.$$

Lemma 7.3 (A positive parallel merge)**.** *Take two endpoint models of heights $R \ge r > 0$, with endpoint masses $\beta, \gamma \ge 0$. Their sum of heat contents is at most that of the single model of height R and total mass $R + \beta + r + \gamma$. The inequality is strict at every positive time.*

Proof. Put $\ell = r + \gamma$. Fractional subtraction in (36) gives

$$p_{R,\beta+\ell} - p_{R,\beta} = \ell z h_{R,\beta} h_{R,\beta+\ell}.$$

By (35), the heat-transform gap for the proposed merge is

$$\frac{p_{R,\beta} + p_{r,\gamma} - p_{R,\beta+\ell}}{z^2} = \frac{p_{r,\gamma}}{z^2} - \frac{\ell h_{R,\beta} h_{R,\beta+\ell}}{z}.$$

Its inverse is the concrete CDF difference

$$\ell\left[\mathbb{P}(\tau_{\mathrm{unif},r,\gamma} \le t) - \mathbb{P}(T_{R,\beta} + T'_{R,\beta+\ell} \le t)\right], \tag{39}$$

where the two terms in the sum are independent. The stochastic chain

$$\tau_{\mathrm{unif},r,\gamma} \le_{\mathrm{st}} T_{r,\gamma} \le_{\mathrm{st}} T_{R,\beta+\ell} \le_{\mathrm{st}} T_{R,\beta} + T'_{R,\beta+\ell}$$

uses $\gamma \le \beta + \ell$ and (38). It proves the sign of (39). Its sign is strict: the last endpoint law has a strictly positive density by Lemma 7.1, whereas the independent added time $T_{R,\beta}$ is strictly positive almost surely. Adding it strictly reduces that CDF at every $t > 0$. Transform uniqueness and continuity identify (39) with the actual heat gap. □

The tree induction consumes this merge in the response form used by the next lemma. For a finite rooted load X, that is, a finite union of singly rooted graphs and endpoint models $E(r,\beta)$ glued only at a common root, write p_X for its root response and M_X for its total speed mass. Write $X \vee Y$ for two loads glued only at their common root.

Lemma 7.4 (Merge lemma for root responses)**.**

(i) $p_{X\vee Y} = p_X + p_Y$ *and* $M_{X\vee Y} = M_X + M_Y$.

(ii) If loads X_i, X_i', $1 \le i \le m$, satisfy $M_{X_i} = M_{X_i'}$ and $(p_{X_i} - p_{X_i'})/z^2$ is the Laplace transform of a nonnegative function K_i, then $X_1 \vee \cdots \vee X_m$ and $X_1' \vee \cdots \vee X_m'$ have equal masses and their response difference divided by z^2 is the transform of $\sum_i K_i \ge 0$.

(iii) Let $R \ge r > 0$, $\beta, \gamma \ge 0$ and $\ell = r + \gamma$. Then $E(R, \beta) \vee E(r, \gamma)$ and $E(R, \beta + \ell)$ have equal mass $R + \beta + \ell$, and

$$\frac{p_{R,\beta}(z) + p_{r,\gamma}(z) - p_{R,\beta+\ell}(z)}{z^2} = \int_0^\infty e^{-zt} K_{\mathrm{m}}(t)\,\mathrm{d}t \qquad (z > 0),$$

where K_{m} is the function (39). It is nonnegative, and strictly positive at every $t > 0$.

For two loads of equal mass, $(p_X - p_{X'})/z^2$ is the transform of $\mathcal{Q}_{X'} - \mathcal{Q}_X$, by (35). Thus (iii) is the hypothesis of Lemma 7.5 for the pair $E(R, \beta) \vee E(r, \gamma)$, $E(R, \beta + \ell)$, including its strict form.

Proof. (i) The absorption solution v_z equals one at the common root, and the two loads meet only there. Hence it solves the separate problems on X and on Y, and the outward root derivatives add. Masses add because the root carries no speed mass. (ii) Apply (i) repeatedly and use linearity of the Laplace transform. (iii) The mass identity is immediate. By (i) the response of the glued pair is $p_{R,\beta} + p_{r,\gamma}$. The displayed transform identity is the computation in the proof of Lemma 7.3: there $p_{r,\gamma}/z^2$ is the transform of ℓ times the uniform-start absorption CDF, by (35), and $\ell h_{R,\beta} h_{R,\beta+\ell}/z$ is the transform of ℓ times the CDF of $T_{R,\beta} + T'_{R,\beta+\ell}$. The sign and strictness are proved there. The final assertion follows from (35), since $J_X - J_{X'} = (p_{X'} - p_X)/z^2$ when $M_X = M_{X'}$. □

Lemma 7.5 (Preservation through a common stem)**.** *Suppose two rooted loads have equal mass and their response difference $(p_1 - p_2)/z^2$ has a nonnegative inverse kernel K. Attaching the same stem preserves this property. If $K(t) > 0$ for every $t > 0$, its propagated kernel has that property as well.*

Proof. For a stem of length $a > 0$, direct solution gives the new response

$$\mathcal{M}_a(p) = \frac{k \tanh(ka) + p}{1 + (p/k)\tanh(ka)}.$$

Its difference factors exactly as

$$\mathcal{M}_a(p_1) - \mathcal{M}_a(p_2) = (p_1 - p_2) h_1 h_2, \qquad h_i = \frac{1}{\cosh(ka) + (p_i/k)\sinh(ka)}.$$

Each h_i is the absorption-time transform from the stem/load junction in the corresponding positive rooted object. The load's boundary value multiplies its unit-root absorption solution, so its flux is that value times p_i; the stem equation yields the displayed formula. The new inverse kernel is therefore K convolved with two probability measures. Equal masses make it exactly the new heat-content gap.

For strictness those measures have mass in $(0, t)$ for every $t > 0$. Indeed a load of mass M has $0 \le p_i(z) \le zM$, by (35) and $0 \le v_z \le 1$. Thus

$$\frac{e^{-a\sqrt{z}}}{1 + M\sqrt{z}} \le h_i(z) \le \operatorname{sech}(a\sqrt{z}) \qquad (z > 0).$$

The upper bound excludes an atom at zero. The lower bound gives $-\log h_i(z)/z \to 0$ and excludes a positive support gap, since support in $[\varepsilon, \infty)$ would force $h_i(z) \le e^{-\varepsilon z}$. Their convolution also has mass in every $(0, t)$, proving the strict assertion. A zero-length stem leaves the kernel unchanged. □

Theorem 7.6 (Sharp rooted-tree heat envelope)**.** *Let T be a finite compact connected metric tree of length $L > 0$, with one Dirichlet vertex and Kirchhoff conditions at every other vertex. Let R be its maximum distance from the Dirichlet vertex. Then*

$$\mathcal{Q}_T(t) \le Q_{R,L-R}(t) \qquad (t > 0). \tag{40}$$

For each fixed $0 < R < L$, the right side is the exact supremum over these trees, approached uniformly on positive compact time windows by the same finite broom sequence. Every finite tree satisfies strict inequality when $R < L$. At $R = L$ the DN interval attains the envelope.

Proof. A rooted edge is the endpoint model with zero endpoint mass. Induct from the leaves toward the root. At each branch, replace the child branches by their endpoint models with the same masses and heights. Their already nonnegative response-gap kernels add under parallel gluing, by Lemma 7.4(ii). Lemma 7.4(iii), repeated from a branch of maximum height, replaces these models by one endpoint model with the sum of their masses and the maximum of their heights; each repetition adds a further nonnegative kernel. Lemma 7.5 propagates the comparison along the next stem. Appending a stem of length a to $E(r, \beta)$ gives exactly $E(r + a, \beta)$, so the actual subtree height and mass are preserved. The finite induction also covers a root of degree greater than one, where the last operation is a parallel merge at the root. Each step supplies a nonnegative inverse response kernel, proving (40). If $R < L$ there is a genuine parallel merge; otherwise the rooted tree is a DN path up to degree-two subdivision. The strict merge and common-stem lemmas propagate strictness to the root.

For sharpness fix $\beta = L - R > 0$, and take the brooms already used in (15), with $b_n = \beta/(n-1)$, $a_n = R - b_n > 0$ and n arms. Their length and height are exactly L, R. Their responses converge for every $z > 0$ to $p_{R,\beta}(z)$. Their absorption laws for uniform initial arclength have transforms $p_n(z)/(zL)$, which converge to the actual model law with initial distribution $(\,\mathrm{d}x + \beta\delta_R)/L$. The limiting probability transform is continuous at zero, with value one, because $p_{R,\beta}(z) \sim zL$. The Laplace continuity theorem for probability measures gives weak convergence of these absorption laws. The model CDF is continuous: its survival is $Q_{R,\beta}(t)/L$, and this heat content is the Laplace integral of a finite positive spectral measure of total mass L. Thus $\mathcal{Q}_{T_n}(t) \to Q_{R,\beta}(t)$ for every $t > 0$.

All the corresponding spectral measures have mass L, so

$$|\mathcal{Q}'_{T_n}(t)| \le \frac{L}{et}, \qquad |Q'_{R,\beta}(t)| \le \frac{L}{et}.$$

These follow from $\sup_{\lambda \ge 0} \lambda e^{-t\lambda} = 1/(et)$. A finite-grid argument upgrades pointwise convergence to uniform convergence on every compact positive time window. This proves the stated supremum with a single sequence. At $R = L$ use the DN interval. □

Corollary 7.7 (The optimal cubic tree endpoint)**.** *For every $0 < \tau_0 \le \tau_1 < \infty$ there is $c > 0$ such that every rooted tree in Theorem 7.6 satisfies, with $\beta = 1 - R/L$ and $\delta_T(\tau) = [\mathcal{Q}_{I_L}(L^2\tau) - \mathcal{Q}_T(L^2\tau)]/L$,*

$$\delta_T(\tau) \ge \frac{c}{24}\beta^3, \qquad d_m(T/L, I_1) \le 2\left(\frac{24\delta_T(\tau)}{c}\right)^{1/3} \qquad (\tau \in [\tau_0, \tau_1]).$$

The exponent $1/3$ is optimal, already on a fixed tree topology.

Proof. Normalize length to one. Theorem 7.6 and (34) give the first inequality. Theorem 4.2 gives $d_m \le 2\beta$, proving the second. The pitchforks in Theorem 10.1 belong to this class, have deficit asymptotic to $2b^3 f(\tau) > 0$ and $d_m \ge b/2$ by (64). For any exponent greater than $1/3$, the corresponding ratio diverges as $b \downarrow 0$. Thus $1/3$ itself is admissible and optimal. □

The same conclusions hold when finitely many selfloops are attached at vertices of a singly rooted tree. Cutting each loop at its midpoint into two equal reflecting stubs preserves constant-data heat content, as in [2, Proposition 6.4] (numbering of arXiv:2502.09461v1). Directly, reflection along the loop fixes the rest of the graph and the initial datum; uniqueness makes the heat solution symmetric, with zero derivative at the midpoint. Its two attachment fluxes are unchanged after the cut. Length is preserved, and the maximum root distance on a loop of length ℓ is the distance of its attachment plus $\ell/2$, also preserved by the two stubs. Repeating this operation gives a rooted tree with the same L, R and heat content.

7.3 Moving excess speed mass toward the leaves

The response argument also applies after a positive redistribution of speed mass. We first keep the energy and rooted metric tree fixed. Let $\mathcal{E}(f,f) = \sum_e \int_e |f'|^2 \, \mathrm{d}y$, with zero trace at the single root, and let the speed measure $\mu \geq \mathrm{d}y$ have a positive piecewise bounded density and finitely many nonroot atoms. Heat content uses initial datum one and the full measure μ. These are classical speed-measure realizations of one-dimensional diffusions; endpoint reservoirs and response reduction have established antecedents [10, 11].

Lemma 7.8 (Ancestor-to-descendant mass relocation)**.** *Let x be an ancestor of v in the rooted tree. Moving a nonnegative amount of excess speed mass from x to v, while retaining $\mu \geq \mathrm{d}y$, cannot decrease heat content at any positive time. More generally the same conclusion holds when a finite nonnegative excess measure supported on an edge is moved to a leaf descended from that edge.*

Proof. For $z > 0$ put $u_\mu = (H_\mu + z)^{-1}\mathbf{1}$ and $h_\mu(w) = 1 - z u_\mu(w) = \mathbb{E}_w e^{-z\tau_0}$, where τ_0 is absorption at the root. The common anchored H^1 variational identity is

$$J_\mu(z) = \sup_f \left\{ 2\int f \, \mathrm{d}\mu - \mathcal{E}(f,f) - z\int f^2 \, \mathrm{d}\mu \right\}.$$

Its unique maximizer gives the measure derivative

$$D_\mu J[\delta_w] = 2u_\mu(w) - z u_\mu(w)^2 = \frac{1 - h_\mu(w)^2}{z}.$$

A path from v to the root must first hit x. The strong Markov property therefore gives $h_\mu(v) = \eta_\mu(v \to x; z) h_\mu(x)$, where η is the first-hitting-time probability transform. Hence

$$D_\mu J[\delta_v - \delta_x] = h_\mu(x)^2 \frac{1 - \eta_\mu(v \to x; z)^2}{z}. \tag{41}$$

The first factor is the transform of the sum of two independent root absorption times started at x. The second is the transform of the survival function of the sum of two independent v-to-x hitting times. Thus the derivative has a specified nonnegative inverse convolution. All these laws refer to the same current measure μ.

For the distributed assertion, let λ be the mass to be moved and interpolate

$$\mu_\theta = \mu_{\mathrm{base}} + (1-\theta)\lambda + \theta\lambda(T)\delta_v, \qquad 0 \leq \theta \leq 1, \qquad \mu_{\mathrm{base}} \geq \mathrm{d}y.$$

The forms $\mathcal{E} + z\mu_\theta$ act on one anchored H^1 space and are uniformly coercive. Point traces and integration against these finite bounded measures are bounded there. Differentiating their Lax–Milgram equations, or taking the variational difference quotient, justifies

$$\frac{\mathrm{d}J_{\mu_\theta}(z)}{\mathrm{d}\theta} = \int \frac{h_{\mu_\theta}(x)^2 - h_{\mu_\theta}(v)^2}{z} \, \lambda(\mathrm{d}x).$$

For real $z > 0$, the common form equations give continuous $u_{\mu_\theta}(x)$ and positive continuous $h_{\mu_\theta}(x; z)$. The quotient $\eta = h(v)/h(x)$ is continuous as well. Probability Laplace continuity makes the corresponding absorption and hitting laws weakly continuous in (θ, x), so their survival-convolution kernels are Borel measurable. Each inverse kernel in (41) lies between zero and one. Tonelli over the finite measure λ and $0 \le \theta \le 1$ therefore identifies a nonnegative inverse for $J_{\mu_1} - J_{\mu_0}$. The actual heat contents are continuous at positive times, and transform uniqueness proves their pointwise order there. This is an averaged heat-content comparison; no ordering of every individual clock trajectory is required. □

Theorem 7.9 (Weighted trees and resistance height)**.** *Let a finite metric tree have one Dirichlet root and, on each physical edge of length $\ell_e > 0$, identical energy and speed density $c_e \ge 1$:*

$$\mathcal{E}(f, f) = \sum_e c_e \int_e |f_x|^2 \, \mathrm{d}x, \qquad \mu = \sum_e c_e \, \mathrm{d}x.$$

Set

$$L = \sum_e c_e \ell_e, \qquad S = \max_v \sum_{e \in [0,v]} \frac{\ell_e}{c_e}, \qquad R = \max_v \sum_{e \in [0,v]} \ell_e.$$

Then, for every $t > 0$,

$$\mathcal{Q}_T(t) \le Q_{S,L-S}(t) \le Q_{R,L-R}(t).$$

Proof. On each edge put $y = x/c_e$. The energy becomes ordinary arclength energy on a tree of edge lengths ℓ_e/c_e, while the speed measure becomes $c_e^2 \, \mathrm{d}y \ge \mathrm{d}y$. Its total mass is still L and its rooted height is $S \le R \le L$. The actual interior generator in this coordinate is $c_e^{-2} d^2/dy^2$; the reference Brownian normalization in the time change is d^2, with no factor $1/2$.

Apply Lemma 7.8 to move the excess measure $(c_e^2 - 1) \, \mathrm{d}y$ on each edge to any leaf descended from that edge. There are finitely many edges. Energy, rooted height and total mass remain fixed, and heat content cannot decrease. The result is an ordinary energy tree with nonnegative leaf masses. The preceding tree response induction applies verbatim: a leaf edge of length a with mass m is the base endpoint model $E(a, m)$; parallel merging and common-stem preservation retain the same mass and height. Thus its heat content is at most $Q_{S,L-S}$. Positive radius variation gives the second inequality. □

Corollary 7.10 (Exact tree quotients)**.** *Suppose a finite standard metric graph with a single Dirichlet root admits a finite root-preserving isometry group whose metric quotient, after subdividing edge-reflection midpoints, is a tree. Then*

$$\mathcal{Q}_G(t) \le Q_{R,L-R}(t) \qquad (t > 0),$$

where L is its original total length and R its original root inradius. The uniform cubic heat-deficit and exponent-$1/3$ geometric estimates hold for this class as well.

Proof. The constant initial datum and rooted operator are group invariant, so uniqueness makes the heat solution invariant. On each quotient edge, energy and speed are both multiplied by its orbit multiplicity $c_e \ge 1$. Summing the original Kirchhoff equations gives precisely the weighted quotient flux condition; an edge-reflection midpoint gives a Neumann leaf. Thus the invariant form and its L^2 space are exactly the weighted tree of Theorem 7.9, and their heat contents agree. Total mass equals the original length. Since the group fixes the root, quotient distance from its root orbit is the original distance from the root. Hence its physical height is R. Apply the theorem and the positive model cubic reserve, followed by the already proved bound $d_m \le 2(1 - R/L)$ after normalization. □

For example, take an equilateral complete graph K_n, $n \geq 3$, with one Dirichlet vertex and edge length ℓ. Permuting the other $n-1$ vertices gives a quotient stem of length ℓ and multiplicity $n-1$. The nonroot edges fold at their midpoints into one pendant edge of length $\ell/2$ and multiplicity $(n-1)(n-2)$. These give

$$L = \frac{n(n-1)}{2}\ell, \qquad R = \frac{3}{2}\ell.$$

At the quotient junction, the weighted flux equation is the sum of the original equations. This supplies cyclic examples of arbitrarily large cycle rank under the exact quotient hypothesis.

The quotient also carries the resistance height of Theorem 7.9, which sharpens the envelope.

Corollary 7.11 (Resistance-height bound on tree quotients)**.** *In the setting of Corollary 7.10, let the quotient tree have edge lengths ℓ_e and orbit multiplicities $c_e \geq 1$, and let*

$$S = \max_v \sum_{e \in [0,v]} \frac{\ell_e}{c_e}$$

be its resistance height, the maximum over quotient vertices v of the sum along the path from the root. Then $0 < S \leq R$ and

$$\mathcal{Q}_G(t) \leq Q_{S,L-S}(t) \leq Q_{R,L-R}(t) \qquad (t > 0). \tag{42}$$

For every $0 < \tau_0 \leq \tau_1 < \infty$, with the constant c of Proposition 7.2,

$$\frac{\mathcal{Q}_{I_L}(L^2\tau) - \mathcal{Q}_G(L^2\tau)}{L} \geq \frac{c}{24}\Big(1 - \frac{S}{L}\Big)^3 \qquad (\tau \in [\tau_0, \tau_1]).$$

Proof. The proof of Corollary 7.10 identifies the heat content of G with that of the weighted tree of Theorem 7.9 whose edge lengths are ℓ_e and whose common energy and speed multiplicities are c_e. Its total mass is L and its physical height is R. The quantity S is exactly the resistance height in that theorem, which gives (42); $S \leq R$ because every $c_e \geq 1$.

For the cubic estimate, scaling lengths and endpoint masses by L^{-1} and time by L^{-2} multiplies the heat content of the endpoint model by L^{-1}, so $Q_{S,L-S}(L^2\tau) = LQ_{S/L,1-S/L}(\tau)$; likewise $\mathcal{Q}_{I_L}(L^2\tau) = L\mathcal{Q}_{I_1}(\tau)$. If $S < L$, (42) and (34) with R replaced by $S/L \in (0,1)$ give the estimate; the constant in (34) depends only on the window. If $S = L$, the right side is zero and the estimate follows from Theorem 5.3. □

For the complete graph K_n above,

$$S = \frac{\ell}{n-1} + \frac{\ell/2}{(n-1)(n-2)} = \frac{(2n-3)\,\ell}{2(n-1)(n-2)}, \qquad \frac{S}{L} = \frac{2n-3}{n(n-1)^2(n-2)},$$

whereas $R/L = 3/(n(n-1))$. Thus $S/R = (2n-3)/(3(n-1)(n-2)) < 1$ for every $n \geq 3$. For $n = 3$, $1 - S/L = 3/4$ against $1 - R/L = 1/2$, so the cubic reserve of Corollary 7.11 is $27/8$ times that of Corollary 7.10.

8 Effective almost-cubic heat stability

We retain the graph model and the marked measured distance of Theorem 4.2. First normalize total length to one and set

$$\Delta_G(t) = \mathcal{Q}_I(t) - \mathcal{Q}_G(t), \qquad R = \max_{x \in G} \operatorname{dist}(x, D), \qquad \beta = 1 - R.$$

The initial datum is $\mathbf{1}$, and the generator is d^2/dx^2. Fix a positive compact observation window $0 < \tau_0 \le \tau_1 < \infty$, and put

$$T = \frac{\tau_0}{2}, \qquad c = \min_{\substack{T \le h \le \tau_1 \\ 0 \le y \le 1}} \frac{K(h;1,y)}{y} > 0. \tag{43}$$

Here K is the fixed mixed mass-coordinate kernel from Theorem 5.3; at $y = 0$ the quotient is its positive inward derivative. Lemma 6.1 justifies this constant and gives

$$\int_0^T \Delta_G(t)\,\mathrm{d}t \le \frac{\Delta_G(t_0)}{c}, \qquad t_0 \in [\tau_0, \tau_1]. \tag{44}$$

No graph-dependent heat-kernel minimum occurs in (43).

Theorem 8.1 (An effective almost-cubic deficit)**.** *For $0 < \beta < 1$, define*

$$\ell = \log(1/\beta), \qquad s_\beta = \frac{2 + \sqrt{4 + T(3\ell + \log 2)}}{T}. \tag{45}$$

Every graph in the stated model satisfies, uniformly for $t_0 \in [\tau_0, \tau_1]$,

$$\Delta_G(t_0) \ge \frac{c}{6}\,\beta^3 \frac{e^{-2s_\beta}}{(1+s_\beta)^2}. \tag{46}$$

At $\beta = 0$ the right side is defined to be zero. For every $\varepsilon > 0$, the positive constant

$$C_\varepsilon = \frac{c}{6} \exp\left(-\frac{16}{T} - 4\sqrt{\frac{\log 2}{T}} - \frac{12}{\varepsilon T} \right) \tag{47}$$

gives the simpler estimate

$$\Delta_G(t_0) \ge C_\varepsilon \beta^{3+\varepsilon}. \tag{48}$$

The constants depend only on the prescribed time window and ε, not on the number of edges, vertex degrees, or smallest edge length.

Proof. The positive comparison in Theorem 5.3 gives $0 \le \Delta_G(t) \le \mathcal{Q}_I(t)$. The unit DN interval has torsion $\int_0^\infty \mathcal{Q}_I(t)\,\mathrm{d}t = 1/3$. Corollary 3.2, with $z = s^2 > 0$, supplies

$$\int_0^\infty e^{-s^2 t} \Delta_G(t)\,\mathrm{d}t \ge \frac{\beta^3 \operatorname{sech}^2 s}{3(1+s)^2} \ge \frac{\beta^3 e^{-2s}}{3(1+s)^2}. \tag{49}$$

The last inequality uses $\cosh s \le e^s$. Independently, splitting this weighted integral at T and using (44) yields

$$\begin{aligned} \int_0^\infty e^{-s^2 t} \Delta_G(t)\,\mathrm{d}t &\le \int_0^T \Delta_G(t)\,\mathrm{d}t + e^{-s^2 T} \int_T^\infty \mathcal{Q}_I(t)\,\mathrm{d}t \\ &\le \frac{\Delta_G(t_0)}{c} + \frac{e^{-s^2 T}}{3}. \end{aligned} \tag{50}$$

Combining (49) and (50) proves, for every $s > 0$,

$$\Delta_G(t_0) \ge \frac{c}{3} \left[\frac{\beta^3 e^{-2s}}{(1+s)^2} - e^{-Ts^2} \right]. \tag{51}$$

This is a time split combined with a separate backward estimate; the pointwise lower bound comes from the backward estimate at the observation time.

For $\beta > 0$, the number in (45) solves

$$Ts_\beta^2 - 4s_\beta = 3\ell + \log 2.$$

Thus

$$e^{-Ts_\beta^2} = \frac{\beta^3}{2} e^{-4s_\beta} \le \frac{\beta^3}{2} \frac{e^{-2s_\beta}}{(1+s_\beta)^2},$$

because $\log(1+s) \le s$ for $s \ge 0$. Substitution into (51) proves (46) for all $0 < \beta < 1$, without a smallness threshold. The case $\beta = 0$ follows from nonnegativity.

For the algebraic form, the elementary square-root inequality gives

$$s_\beta \le \frac{4}{T} + \sqrt{\frac{3\ell}{T}} + \sqrt{\frac{\log 2}{T}}.$$

Also $2s + 2\log(1+s) \le 4s$, and Young's inequality gives

$$4\sqrt{\frac{3\ell}{T}} \le \varepsilon\ell + \frac{12}{\varepsilon T}.$$

Consequently

$$2s_\beta + 2\log(1+s_\beta) \le \frac{16}{T} + 4\sqrt{\frac{\log 2}{T}} + \varepsilon\ell + \frac{12}{\varepsilon T}.$$

Exponentiating this inequality in (46), and using $e^{-\varepsilon\ell} = \beta^\varepsilon$, proves (48) with precisely (47). □

Corollary 8.2 (Every geometric Hölder exponent below one third)**.** *For every $0 < \alpha < 1/3$, let $\varepsilon = 1/\alpha - 3 > 0$. Then*

$$\beta \le C_\varepsilon^{-\alpha} \Delta_G(t_0)^\alpha, \qquad d_m(G, I) \le 2C_\varepsilon^{-\alpha} \Delta_G(t_0)^\alpha \quad (t_0 \in [\tau_0, \tau_1]). \tag{52}$$

For a graph of original length L, replace β by $1 - R/L$, use the dimensionless observation window for t/L^2, and replace $\Delta_G(t)$ by

$$\frac{\mathcal{Q}_{I_L}(t) - \mathcal{Q}_G(t)}{L}.$$

Distances and arclength measure are normalized by L before using d_m. The same constants then apply.

Proof. Raise (48) to the power $\alpha = 1/(3+\varepsilon)$, then apply Theorem 4.2, which gives $d_m \le 2\beta$. Metric rescaling multiplies lengths by L^{-1}, time by L^{-2}, and heat content by L^{-1}, proving the final assertion. □

Remark 8.3 (Effective selection of the interval constant)*.* For computable positive window parameters, a positive rational number not exceeding the minimum in (43) can be certified from this fixed interval alone. With $k_n = (n + 1/2)\pi$,

$$\frac{K(h; 1, y)}{y} = 2\sum_{n \ge 0} (-1)^n \frac{\sin(k_n y)}{y} e^{-k_n^2 h}, \qquad h \ge T,$$

where the removable quotient at $y = 0$ is k_n. The uniform tail is bounded by $2\sum_{n>N} k_n e^{-Tk_n^2}$. Bounds for the derivatives with respect to h and y are respectively

$$2\sum_{n \ge 0} k_n^3 e^{-Tk_n^2}, \qquad \sum_{n \ge 0} k_n^2 e^{-Tk_n^2}.$$

For the latter, use $\sin(ky)/y = \int_0^k \cos(vy)\,\mathrm{d}v$, including its value at zero. Gaussian integral tails bound these series effectively. Finite rational grids, these Lipschitz and tail bounds, and interval enclosures of the finite trigonometric and exponential terms yield certified uniform lower bounds on the compact cylinder. Its strictly positive true minimum ensures that a finite stage certifies a positive rational lower bound. Any smaller positive rational may be used as c throughout the theorem. This specifies an effective procedure for selecting the constant. For arbitrary real window parameters the inequalities hold for every positive c below the minimum.

Remark 8.4 (Size of the subpower factor). Since $s_\beta = \sqrt{3\log(1/\beta)/T} + O_T(1)$, (46) differs from β^3 by the subpower factor $\exp(-O_T(\sqrt{\log(1/\beta)}))$. Its right side is increasing in β, so it also admits monotone one-dimensional inversion as an effective modulus. The factor comes from the absolute tail in (50), which is balanced against the reserve by the choice $s = s_\beta$. On rooted trees and exact tree quotients the cubic bound $\Delta_G(t_0) \geq C\beta^3$ itself holds, by Corollaries 7.7 and 7.10.

9 An independent formula for the asymmetric pitchfork

Consider a stem of length $a > 0$ joining a Dirichlet leaf to a Kirchhoff junction, with two further arms of lengths $b, c > 0$ ending at Neumann leaves. Write $P = P(a; b, c)$ and $L = a + b + c$. This example admits a separate positive convolution proof. The formulas and the identity of Proposition 9.1 are also [A, Section 6 and Proposition 6.1]; we include the proof because Section 10 uses its factorization. General pendant-edge surgery principles are treated in [2, Section 6] (numbering of arXiv:2502.09461v1).

For $s > 0$ put $k = \sqrt{s}$, $A = \tanh(ka)$, $B = \tanh(kb)$ and $C = \tanh(kc)$. Let $Z_P(s)$ be the Laplace transform of the absorption time for diffusion on P started at the junction, and let $Z_I(s)$ be the corresponding transform on the mixed interval started at distance a from its absorbing endpoint. This point has coordinate $L - a$ in our Neumann-at-zero convention. Solving $Z'' = sZ$, with $Z = 1$ at the absorbing endpoint and the usual conditions elsewhere, gives

$$Z_P(s) = \frac{1}{\cosh(ka) + (B + C)\sinh(ka)}, \qquad Z_I(s) = \frac{\cosh(k(b + c))}{\cosh(kL)}. \tag{53}$$

The same calculation gives the heat-content transforms

$$\widehat{\mathcal{Q}}_P(s) = \frac{L}{s} - \frac{A + B + C}{sk(1 + A(B + C))}, \qquad \widehat{\mathcal{Q}}_I(s) = \frac{L}{s} - \frac{\tanh(kL)}{sk}. \tag{54}$$

For completeness, $\widehat{u} = (1 - Z)/s$ solves the heat resolvent with initial datum one. Integrating $Z'' = sZ$ over the graph cancels all Kirchhoff and Neumann fluxes. On the stem, with distance x from the absorbing endpoint, $Z(x) = \cosh(kx) + d\sinh(kx)$; the junction condition gives $d = -(A+B+C)/(1+A(B+C))$. Hence $\int_P Z = -Z'(0)/s = (A+B+C)/(k(1+A(B+C)))$, proving (54).

Proposition 9.1 (Pitchfork convolution identity)**.** *For $\ell > 0$ define the positive locally integrable function*

$$h_\ell(t) = \frac{2}{\ell}\sum_{n=0}^{\infty} \exp\left(-\frac{(n + 1/2)^2\pi^2 t}{\ell^2}\right), \qquad t > 0.$$

Let μ_P, μ_I be the absorption-time probability measures whose Laplace transforms are (53)*. Then*

$$\mathcal{Q}_I(t) - \mathcal{Q}_P(t) = \big(h_b * h_c * h_{b+c} * \mu_P * \mu_I\big)(t), \qquad t > 0. \tag{55}$$

In particular the deficit is nonnegative, and

$$\int_0^\infty (\mathcal{Q}_I(t) - \mathcal{Q}_P(t))\,\mathrm{d}t = bc(b+c).$$

Proof. The interval mixed eigenfunction expansion, or the partial fraction expansion of tanh, gives

$$\int_0^\infty e^{-st} h_\ell(t)\,\mathrm{d}t = \frac{\tanh(\ell\sqrt{s})}{\sqrt{s}}, \qquad \int_0^\infty h_\ell(t)\,\mathrm{d}t = \ell.$$

The transforms Z_P, Z_I are those of probability measures: absorption is almost sure on these finite anchored graphs. This also follows by letting $s \downarrow 0$ in (53). Subtract (54), use $\tanh(k(b+c)) = (B+C)/(1+BC)$, and simplify to obtain

$$\widehat{\mathcal{Q}}_I(s) - \widehat{\mathcal{Q}}_P(s) = \frac{\tanh(kb)}{k}\frac{\tanh(kc)}{k}\frac{\tanh(k(b+c))}{k}\, Z_P(s) Z_I(s).$$

Tonelli and uniqueness of Laplace transforms prove the convolution identity almost everywhere. It holds everywhere by continuity: $h_\ell(t) = O(t^{-1/2})$ near zero and decays exponentially at infinity, so the triple convolution extends to a continuous bounded function on the real line when set to zero for $t \le 0$. Convolving with the finite measures preserves continuity. Finally integrate by Tonelli and multiply the five total masses. □

10 The cubic pitchfork profile and geometric sharpness

The positive convolution formula also determines the small-arm profile at fixed positive times. This supplies a heat-specific obstruction to improving the geometric exponents, rather than inferring such an obstruction from a stationary integral alone.

Theorem 10.1. *Let $P_b = P(1-2b; b, b)$, $0 < b \le 1/4$, and let I be the unit mixed Dirichlet–Neumann interval. Put*

$$\Delta_b(t) = \mathcal{Q}_I(t) - \mathcal{Q}_{P_b}(t).$$

Let μ be the absorption-time probability law from the reflecting endpoint of I, for the generator $+d^2/dx^2$. There is a continuous strictly positive probability density f on $(0,\infty)$, namely the density of $\mu * \mu$, such that

$$\frac{\Delta_b(t)}{2b^3} \longrightarrow f(t) \qquad (b \downarrow 0), \tag{56}$$

uniformly on every compact subinterval of $(0,\infty)$. Its Laplace transform is

$$\widehat{f}(z) = \operatorname{sech}^2\sqrt{z}, \qquad \Re z > 0, \tag{57}$$

where the square root has positive real part.

Proof. The graph has length one and inradius $1-b$. We use the functions h_ℓ and the absorption transforms from Proposition 9.1 and (53). Since h_ℓ has mass ℓ, h_ℓ/ℓ is a probability density. Its transform

$$\frac{\widehat{h}_\ell(z)}{\ell} = \frac{\tanh(\ell\sqrt{z})}{\ell\sqrt{z}}$$

has modulus at most one on $\Re z > 0$ and tends to one as $\ell \downarrow 0$ for each fixed such z. Write $a = 1-2b$, $k = \sqrt{z}$, and

$$Z_{P,b}(z) = \frac{1}{\cosh(ka) + 2\tanh(kb)\sinh(ka)}, \qquad Z_{I,b}(z) = \frac{\cosh(2kb)}{\cosh k}.$$

The positive convolution identity gives the probability density $f_b(t) = \Delta_b(t)/(2b^3)$, continuous for $t > 0$, and its transform

$$F_b(z) = \left(\frac{\widehat{h}_b(z)}{b}\right)^2 \frac{\widehat{h}_{2b}(z)}{2b}\, Z_{P,b}(z) Z_{I,b}(z). \tag{58}$$

The formulas originally obtained for positive real parameters extend to $\Re z > 0$ by analyticity of these probability transforms. Each absorption factor tends to $1/\cosh k$, so

$$F_b(z) \longrightarrow F(z) = \operatorname{sech}^2 k. \tag{59}$$

We next justify inversion uniformly in b. Fix $\sigma > 0$ and take $z = \sigma + i\omega$, $k = \rho + i\eta$. Then

$$\rho^2 = \frac{|z| + \sigma}{2}, \qquad \rho \geq \sqrt{\sigma}, \qquad \rho \geq \sqrt{|\omega|/2}.$$

The identity

$$\Re \tanh(bk) = \frac{\sinh(2b\rho)}{\cosh(2b\rho) + \cos(2b\eta)} > 0$$

shows that $w = 2\tanh(bk)$ has positive real part. Hence $|1+w| \geq 1$ and $|(1-w)/(1+w)| \leq 1$. Since

$$Z_{P,b}(z) = \frac{2e^{-ka}}{(1+w) + (1-w)e^{-2ka}},$$

and $a \geq 1/2$, we obtain

$$|Z_{P,b}(z)| \leq \frac{2e^{-a\rho}}{1 - e^{-2a\rho}} \leq \frac{2e^{-a\rho}}{1 - e^{-\sqrt{\sigma}}}. \tag{60}$$

Also $|\cosh(2bk)| \leq \cosh(2b\rho) \leq e^{2b\rho}$ and $|\cosh k| \geq \sinh \rho$. Therefore

$$|Z_{I,b}(z)| \leq \frac{2e^{-a\rho}}{1 - e^{-2\rho}} \leq \frac{2e^{-a\rho}}{1 - e^{-\sqrt{\sigma}}}. \tag{61}$$

The three normalized h factors in (58) have modulus at most one. Thus, uniformly for $0 < b \leq 1/4$,

$$|F_b(\sigma + i\omega)| \leq C_\sigma e^{-2a\rho} \leq C_\sigma e^{-\rho} \leq C_\sigma e^{-\sqrt{|\omega|/2}}, \qquad C_\sigma = \frac{4}{(1 - e^{-\sqrt{\sigma}})^2}. \tag{62}$$

This is integrable over $\omega \in \mathbb{R}$. The pointwise limit F has the same bound. Dominated convergence now gives

$$\int_{\mathbb{R}} |F_b(\sigma + i\omega) - F(\sigma + i\omega)|\, d\omega \longrightarrow 0. \tag{63}$$

For clarity, inversion here is ordinary Fourier inversion of an exponentially tilted density. Extend f_b by zero to negative times. Then $e^{-\sigma t} f_b(t)$ is integrable and has Fourier transform $F_b(\sigma + i\omega)$, which is integrable by (62). Fourier inversion identifies its continuous inverse representative. Since the original f_b is continuous for $t > 0$, the almost-everywhere identification holds at every positive time. In particular

$$f_b(t) = \frac{e^{\sigma t}}{2\pi} \int_{\mathbb{R}} e^{i\omega t} F_b(\sigma + i\omega)\, d\omega.$$

The inverse expression with F defines a continuous function f at positive times. For $0 < \tau_0 \leq \tau_1 < \infty$, (63) implies

$$\sup_{t \in [\tau_0, \tau_1]} |f_b(t) - f(t)| \leq \frac{e^{\sigma \tau_1}}{2\pi} \int_{\mathbb{R}} |F_b - F|\, d\omega \longrightarrow 0.$$

The argument uses only the fixed vertical line $\Re z = \sigma$.

It remains to identify the limit and its positivity. For this purpose use coordinates with Dirichlet endpoint 0 and reflecting endpoint 1. Solving $Z'' = zZ$, $Z(0) = 1$, $Z'(1) = 0$ gives $\widehat{\mu}(z) = \operatorname{sech}\sqrt{z}$. The absorption law has a continuous positive density $j(t)$ for $t > 0$. Indeed, if $K_t(1, y)$ is the mixed-interval heat kernel, survival from the reflecting endpoint is $S(t) = \int_0^1 K_t(1, y)\, dy$. The heat equation and its endpoint conditions give

$$j(t) = -S'(t) = \partial_y K_t(1, 0) > 0.$$

The derivative is strictly positive by the parabolic boundary Hopf lemma; positive-time smoothness gives continuity. Also $S(0+) = 1$ and $S(t) \to 0$ at infinity, so j has mass one and there is no atom at zero.

One can verify the continuity needed for convolution directly on the transform side as well. On each line $\Re z = \sigma$, $|\operatorname{sech}\sqrt{z}| \le C'_\sigma e^{-\rho}$ is integrable in ω. Fourier inversion for the exponentially tilted finite measure μ therefore gives a continuous bounded density on the whole real line, agreeing with $e^{-\sigma t} j(t)$ at positive times. Its self-convolution is continuous, since it is both bounded continuous and integrable. Undoing the tilt shows that $j * j$ is continuous on compact positive time intervals. It is strictly positive at every $t > 0$, because both integrand factors in

$$(j * j)(t) = \int_0^t j(s) j(t - s)\, ds$$

are positive on $(0, t)$. It is a probability density and its transform is $F(z)$. Uniqueness of Laplace transforms identifies it with the inverse f above, proving (57) and (56). □

The mark set also gives the reverse geometric comparison

$$\beta/2 \le d_m(G, I) \le 2\beta. \tag{64}$$

Indeed, in any common embedding whose support and mark Hausdorff distances are at most h, match a support point to the other support within h. Its distance to the respective mark set changes by at most another h, because distance to a set is 1-Lipschitz and the mark sets are within h. Taking suprema in both directions gives $|R_G - R_I| \le 2h$. Infimizing over embeddings proves the lower bound; the upper bound is the explicit common embedding in Theorem 4.2.

Corollary 10.2. *At any fixed positive time, no graph-uniform bound*

$$d_m(G, I) \le C(t)[\mathcal{Q}_I(t) - \mathcal{Q}_G(t)]^\alpha$$

can hold for an exponent $\alpha > 1/3$ in the normalized graph class. Together with Corollary 8.2, the supremum of the admissible geometric Hölder exponents on each compact positive time window is exactly $1/3$. On the rooted-tree and exact tree-quotient classes, the endpoint exponent itself is valid by Corollaries 7.7 and 7.10.

Proof. For P_b, the longest root-to-leaf path has length $1 - b$, whereas the two-arm path has length $2b \le 1 - b$. Thus $\operatorname{diam} P_b = 1 - b$. Since $\operatorname{diam} I = 1$, the GH diameter inequality gives

$$d_m(P_b, I) \ge d_{\mathrm{GH}}(P_b, I) \ge b/2.$$

For every fixed $t > 0$, Theorem 10.1 gives $\Delta_b(t) \sim 2f(t)b^3$, with $f(t) > 0$. Hence for $\alpha > 1/3$,

$$\frac{d_m(P_b, I)}{\Delta_b(t)^\alpha} \ge c_t b^{1-3\alpha} \longrightarrow \infty$$

for some $c_t > 0$. This excludes every such exponent, even on this one fixed graph topology. The estimates in Corollary 8.2 provide every $\alpha < 1/3$ uniformly on each prescribed positive time window; together these two directions identify the general-graph supremum. Equivalently, the pitchfork family excludes a uniform lower heat-deficit bound proportional to β^γ for any $\gamma < 3$, while the proved lower bounds cover every $\gamma > 3$. □

On any prescribed positive time window, (64) shows that an endpoint geometric estimate $d_m \le C\Delta^{1/3}$ and a cubic inradius lower bound $\Delta \ge c\beta^3$ are equivalent up to window-dependent constants. Corollaries 7.7 and 7.10 establish these endpoint estimates on the stated rooted-tree and quotient classes. Constants refer to a prescribed positive compact time window.

11 Scope

The results apply to finite compact connected unweighted metric graphs with positive edge lengths, a nonempty Dirichlet vertex set and standard Kirchhoff conditions elsewhere; loops, multiple edges and a disconnected Dirichlet-cut interior are included. The stationary envelope holds for every fixed $1 < p < \infty$, and the resolvent, heat and stability results concern the linear case $p = 2$ with initial datum one. On this whole class the heat deficit at a fixed positive time controls the marked measured distance to the mixed interval with every exponent below $1/3$, with explicit constants depending only on the time window, and the pitchfork profile identifies $1/3$ as the supremum of the admissible exponents. On rooted trees and on graphs with exact root-preserving tree quotients, the sharp heat envelope holds at every positive time and the cubic reserve and the exponent $1/3$ itself hold uniformly; on quotients the resistance height refines the envelope. Weighted trees with matching multiplicities $c_e \ge 1$ obey the same heat envelope in terms of their total mass and their resistance or physical height. The positive response comparison behind these results is preserved by parallel merging, common-stem attachment and ancestor-to-descendant mass relocation.

Editions and the companion paper. This is the first edition of this article. It is a separate work from the companion paper [A], Archive edition 3 of 1 November 2026, which proves the length-only all-times heat-content comparison together with general-data concentration, single-time equality and a double-Dirichlet comparison under a bridge condition. The overlapping material of this article, namely the constant-data source argument of Section 5 and the pitchfork identity of Proposition 9.1, is identified where it occurs. The length–inradius envelopes, the rooted-tree heat envelope, the mass relocation and quotient results, the effective stability estimates and the cubic pitchfork profile are the contributions of this article beyond [A].

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