

Virtuous smoothing for global optimization

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Abstract In the context of global optimization and mixed-integer non-linear programming, generalizing a technique of D’Ambrosio, Fampa, Lee and Vigerske for handling the square-root function, we develop a virtuous smoothing method, using cubics, aimed at functions having some limited non-smoothness. Our results pertain to root functions (w^p with $0 < p < 1$) and their increasing concave relatives. We provide (i) a sufficient condition (which applies to functions more general than root functions) for our smoothing to be increasing and concave, (ii) a proof that when $p = 1/q$ for integers $q \geq 2$, our smoothing lower bounds the root function, (iii) substantial progress (i.e., a proof for integers $2 \leq q \leq 10,000$) on the conjecture that our smoothing is a sharper bound on the root function than the natural and simpler “shifted root function”, and (iv) for all root functions, a quantification of the superiority (in an average sense) of our smoothing versus the shifted root function near 0.

Introduction

Important models for framing and attacking hard (often non-linear) combinatorial-optimization problems are GO (global optimization) and MINLP (mixed-integer non-linear programming). Virtually all GO and MINLP solvers (e.g., **SCIP** [1], **Baron** [23], **Couenne** [4], **Antigone** [18]) apply some variant of spatial branch-and-bound (see, [21], for example), and they rely on NLP (non-linear-programming) solvers, both to solve continuous relaxations (to generate lower bounds for minimization) and often to generate good feasible solutions (to generate upper bounds). Sometimes models are organized to have a convex relaxation, and then either outer

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approximation, NLP-based branch-and-bound, or some hybrid of the two is employed (e.g., **Bonmin** [5]; also see [6]). In such a case, NLP solvers are also heavily relied upon, and for the same uses as in the non-convex case.

Convergence of most NLP solvers (e.g. **Ipopt** [24]) requires that functions be twice continuously differentiable. Yet many models naturally utilize functions with some limited non-differentiability. One approach to handle limited non-differentiability is smoothing.

Of course there is a vast literature on global optimization concerning convexification (see [22]). Such research aims at developing tractable lower bounds for non-convex formulations $z := \min\{f_0(x) : x \in \mathcal{F}\}$. Even when the only non-convexities are integrality of some variables, improving the trivial convexification (relaxing integrality) is crucial to the success of algorithms such as outer-approximation (see [5], for example). But lower bounding z is not the complete story. For example, spatial branch-and-bound (for formulations that are non-convex after relaxing integrality) and outer-approximation (for formulations that are convex after relaxing integrality) both require solutions of the NLPs (convex or not) obtained by relaxing integrality. They do this in an effort to find actual (incumbent) feasible solutions and hence upper bounds on z . The success of this step, requires close approximation of the MINLP and tractability of the NLPs. Our results for smoothing are aimed at getting tractable NLPs in the presence of functions with limited non-differentiability. For univariate concave functions, we aim for concave under-estimation which has the effect of forcing the approximation to be near the function that we approximate. Note that convexifying a univariate concave function via secant under-estimation can do a rather poor job of close approximation. This idea of using one version of a function for convexification in the context of lower bounding z and another version of a function aimed at coming closer to the MINLP was implemented for objective functions in **Bonmin**, in the context of an application; see [7,8] (a study of optimal water-network refurbishment via MINLP). Additionally, it is possible to simply use our smoothing methodology as a formulation pre-processor for a spatial branch-and-bound algorithm. With such a use, the smoothing inherits the convexification structure of the MINLP; that is, our approximation, because of its concavity, allows for secant under-estimation and tangent over-estimation, and this has been implemented in **SCIP** (see §5.2). Furthermore, in the context of smoothing as a pre-processing step, [10,11] used the under-estimation property of our smoothing to get an *a priori* upper-bound on how much the optimal value of their smoothed MINLP could be below z . Finally, also employing smooth concave under-estimators, [20] describes a global-optimization algorithm for univariate functions; so we can see another use of such under estimators in global optimization.

Additionally in [7,8], an ad-hoc smoothing method is used to address non-differentiability near 0 of the Hazen-Williams (empirical) formula for the pressure drop of turbulent water flow in a pipe as a function of the flow. Choosing a small positive δ and fitting an odd homogeneous quintic on $[-\delta, \delta]$, so as to match the function and its first and second derivatives at $\pm\delta$ and the function value at 0, the resulting piecewise function is smooth enough for NLP solvers. However on $(-\delta, \delta)$ the quintic is neither an upper bound nor a lower bound on the function it approximates.

In [16] (a study of the TSP with “neighborhoods”), \sqrt{w} is smoothed (near 0) by choosing again a small positive δ and then using a linear extrapolation of \sqrt{w}

at $w = \delta$ to approximate \sqrt{w} on $[0, \delta]$. Shortcomings of this approach are that the resulting piecewise function is: (i) not twice differentiable at $w = \delta$, and (ii) over-estimates \sqrt{w} on $[0, \delta]$. Regarding (ii), in many formulations (see [10,11], for example), we need an under-estimate of the function we are approximating to get a valid relaxation.

To address the identified shortcomings of the methodology of [16] for smoothing square roots, motivated by developing tractable mixed-integer non-linear-optimization models for the Euclidean Steiner Problem (see [14]), [10,11] developed a virtuous method. On the interval $[0, \delta]$, they fit a homogeneous cubic, to match the function value of the square root at the endpoints, and matching the first and second derivatives at $w = \delta$. They demonstrate that the resulting smooth function, though piecewise defined, is increasing, strictly concave, under-estimates \sqrt{w} on $(0, \delta)$, and is a stronger under-estimate of \sqrt{w} than the more elementary “shift” $\sqrt{w + \lambda} - \sqrt{\lambda}$, for some $\lambda > 0$. To make a fair comparison, δ is chosen as a function of λ so that the two approximating functions have the same derivative at 0. This makes sense because, for each approximation, we would choose the value of the smoothing parameter (δ or λ) as small as the numerics will tolerate — that is, we would have an upper bound for the derivative of the approximation (at zero, where it is greatest).

For the $\sqrt{\cdot}$ function, we have depicted all of these smoothings in Figure 1. From top to bottom: The “linear extrapolation” follows the dot-dashed line ($\cdot\text{---}\cdot$) below $\delta = 0.1$. The solid curve (—) is the true $\sqrt{\cdot}$. The “smooth under-estimation”, which we advocate, follows the dotted curve ($\cdot\cdots\cdot$) below $\delta = 0.1$. The “shift”, chosen to have the same derivative as our preferred smoothing at 0, follows the weaker under-estimate (on the entire non-negative domain) given by the dashed curve (-- --).

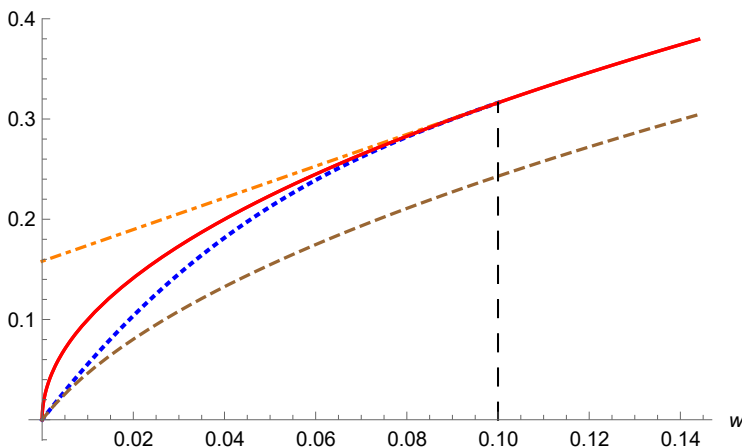


Fig. 1: Behavior of all smoothings of the square root

Most of our results are for root functions (w^p with $0 < p < 1$) and their increasing concave relatives. Smoothing roots (not just square roots) can play an important role in working with ℓ_q norms ($q > 1$) and quasi-norms ($0 < q < 1$): $\ell_q(x) := (\sum_j x_j^q)^{1/q}$. Depending on q (less than 1, or greater than 1), each inner

power or the outer power is a root function. Of course the use of norms is quite common. Additionally, in sparse optimization, ℓ_q quasi-norms are used to induce sparsity; see, for example, [17] and the references therein. So, our work can be used to apply global-optimization techniques in this important setting. Additionally, root functions are natural for fitting nearly-smooth functions to data that follows an increasing concave trend; for example, cost functions with economies of scale, and the well-known Cobb-Douglas production function (and generalizations), relating production to labor and capital inputs, where the exponents of the inputs are the output elasticities (see [12] and [3]). After such a data-analysis step, fitted functions can be incorporated into optimization models, and our results would then be applicable; also see [9] for a modern data-driven integrated function-fitting/optimization methodology. Additionally, roots occur in other sigmoidal functions besides the Cobb-Douglas production function (see [13]). Finally, besides root functions, there are other simple univariate building-block functions that our scheme applies to; for example $\log(1+w)$ and $\text{ArcSinh}(\sqrt{w})$ (see Examples 6 and 7).

In §1, we provide a sufficient condition (which applies to functions more general than root functions) for our smoothing to be increasing and concave. Moreover, we give an interesting example to illustrate that when our condition is not satisfied, the conclusion need not hold. In §2, we establish that when $p = 1/q$ for integers $q \geq 2$, our smoothing lower bounds the root function. Having such control over the root function is important in the context of global optimization — in fact, this was a key motivation of [10, 11]. In §3, we present substantial progress (i.e., a proof for integers $2 \leq q \leq 10,000$) on the conjecture that our smoothing is a sharper bound on the root function than the natural and simpler “shifted root function”. In §4 we quantify the average relative performance of our smoothing and of the shifted root function near 0. We demonstrate that our smoothing is much better with respect to this performance measure. Finally, in §5, we make some concluding remarks: describing alternatives, available software, some extended use, and our ongoing work.

1 General smoothing via a homogenous cubic

1.1 Construction of our smoothing

We are given a function f defined on $[0, +\infty)$ having the following properties: $f(0) = 0$, f is increasing and concave on $[0, +\infty)$, $f'(w)$ and $f''(w)$ are defined on all of $(0, +\infty)$, but $f'(0)$ is undefined. For example, the *root function* $f(w) := w^p$, with $0 < p < 1$, has these properties. Our goal is to find a function g that mimics f well, but is differentiable everywhere (in particular at 0). In addition, because our context is global optimization, we want g to lower bound f on $[0, +\infty)$. In this way, we can develop smooth relaxations of certain optimization problems involving f .

The definition of our function g depends on a parameter $\delta > 0$. Our function g is simply f on $[\delta, +\infty)$. This parameter δ allows us to control the derivative of g at 0. Essentially, lowering δ increases the derivative of g at 0, and so in practice, we choose δ as low as the numerics will tolerate.

We extend g to $[0, \delta]$, as a homogeneous cubic, so that $g(0) = f(0) = 0$, $g(\delta) = f(\delta)$, $g'(\delta) = f'(\delta)$ and $g''(\delta) = f''(\delta)$. The homogeneity immediately gives us $g(0) = 0$, and such a polynomial is the lowest-degree one that allows us to match f , f' and f'' at δ . We choose the three coefficients of $g(w) := Aw^3 + Bw^2 + Cw$ so that the remaining three conditions are satisfied.

The constants A , B and C are solutions to the system:

$$\begin{aligned} (g(\delta) =) \quad & \delta^3 A + \delta^2 B + \delta C = f(\delta) \\ (g'(\delta) =) \quad & 3\delta^2 A + 2\delta B + C = f'(\delta) \\ (g''(\delta) =) \quad & 6\delta A + 2B = f''(\delta). \end{aligned}$$

We find that

$$\begin{aligned} A &= \frac{f(\delta)}{\delta^3} - \frac{f'(\delta)}{\delta^2} + \frac{f''(\delta)}{2\delta}, \\ B &= -\frac{3f(\delta)}{\delta^2} + \frac{3f'(\delta)}{\delta} - f''(\delta), \\ C &= \frac{3f(\delta)}{\delta} - 2f'(\delta) + \frac{\delta f''(\delta)}{2}. \end{aligned}$$

By construction, we have the following result.

Proposition 1 The constructed function g has $g(0) = 0$, $g(\delta) = f(\delta)$, $g'(\delta) = f'(\delta)$ and $g''(\delta) = f''(\delta)$.

1.2 Increasing and concave

Mimicking f should mean that g is increasing and concave on all of $[0, +\infty)$. Next, we give a sufficient condition for this. The condition is a bound on the amount of negative curvature of f at δ .

Theorem 2 Let $\delta > 0$ be given. On $[\delta, +\infty)$, let f be increasing and differentiable, with f' non-increasing (decreasing). Let $f(0) = 0$, and let f be twice differentiable at δ . If

$$f''(\delta) \geq \frac{2}{\delta} \left(f'(\delta) - \frac{f(\delta)}{\delta} \right), \quad (T_\delta)$$

the associated function g is increasing and concave (strictly concave) on $[0, +\infty)$.

Proof For $w \in [0, \delta]$, the third derivative of g is the constant

$$g'''(w) = \frac{6}{\delta^3} \left(f(\delta) - \delta f'(\delta) + \frac{\delta^2}{2} f''(\delta) \right).$$

The first factor is clearly positive. The inequality requirement on $f''(\delta)$ in our hypothesis makes the second factor non-negative. We conclude that the third derivative of g is non-negative, implying that the second derivative of g is non-decreasing to a non-positive (negative) value, $g''(\delta) = f''(\delta)$, on the interval $[0, \delta]$. Consequently, $g'(w)$ is non-increasing (decreasing) to $g'(\delta) = f'(\delta) > 0$.

Note that the assumptions on f imply that for $w \in [\delta, +\infty)$, $g'(w) = f'(w)$ is non-increasing (decreasing) and $g'(w) = f'(w) > 0$. Therefore, g is concave (strictly concave) and increasing on $[0, +\infty)$. \square

Root functions, that is power functions of the form $f(w) = w^p$ with $0 < p < 1$, fit our general framework: $f(0) = 0$, f is increasing and concave on $[0, +\infty)$, $f'(w)$ and $f''(w)$ are defined on all of $(0, +\infty)$, but $f'(0)$ is undefined. Indeed, our work was inspired by the construction for $p = 1/2$ in [10,11]. Next, we verify that Theorem 2 applies to root functions.

Lemma 3 For $f(w) = w^p$, $0 < p < 1$, we have that f satisfies T_δ for all $\delta > 0$.

Proof For $f(w) = w^p$, the inequality T_δ is

$$p(p-1)\delta^{p-2} \geq \frac{2}{\delta} \left(p\delta^{p-1} - \frac{\delta^p}{\delta} \right),$$

which simplifies to $(p-1)(p-2) \geq 0$, and which is satisfied because $p < 1$ \square

So, by Theorem 2, we have the following result.

Corollary 4 For $f(w) = w^p$, $0 < p < 1$, the associated g is increasing and strictly concave on $[0, +\infty)$.

The following very useful fact is easy to see.

Lemma 5 The set of f with domain $[\delta, +\infty)$ satisfying any of

- $f(0) = 0$,
- f is increasing,
- f is differentiable,
- f' is non-increasing or decreasing,
- f is twice differentiable at δ ,
- T_δ

is a (blunt) cone in function space.

As a consequence of Lemma 5 and Corollary 4, adding a root function to any f that is differentiable at 0 and satisfies *all* of the properties listed in Lemma 5, we get such a function that is non-differentiable at 0 and has decreasing first derivative.

Next, we give a couple of natural examples to demonstrate that Theorem 2 applies to other functions besides root functions.

Example 6 Let $f(w) := \log(1+w)$, which is clearly concave and increasing on $[0, +\infty)$, and has $f(0) = 0$. To verify that T_δ is satisfied for $\delta > 0$, we consider the expression $f''(\delta) - \frac{2}{\delta} \left(f'(\delta) - \frac{f(\delta)}{\delta} \right)$, which simplifies to

$$\frac{2(1+\delta)^2 \log(1+\delta) - 3\delta^2 - 2\delta}{\delta^2(1+\delta)^2}.$$

The denominator of this expression is positive so we focus on the numerator, which we define to be $k(\delta)$. The second derivative of the numerator, $k''(\delta) = 4 \log(1+\delta)$, is positive for $\delta > 0$, implying that the $k'(\delta) = 4(1+\delta) \log(1+\delta) - 6\delta$ increases from $k'(0) = 0$. Therefore, $k(\delta)$ likewise increases from $k(0) = 0$. We conclude that T_δ is satisfied for $\delta > 0$. Note that by Lemma 5, we can add \sqrt{w} to f to get an example that is not differentiable at 0. \diamond

Example 7 Let $f(w) := \text{ArcSinh}(\sqrt{w}) = \log(\sqrt{w} + \sqrt{1+w})$ on $[0, +\infty)$. Clearly $f(0) = 0$. We have $f'(w) = 1/(2\sqrt{w}\sqrt{w+1})$, which is non-negative on $(0, +\infty)$, so f is increasing, but it is not differentiable at 0. Additionally, $f''(x) = (-2x - 1)/(4x^{3/2}(x+1)^{3/2})$, which is clearly negative on $(0, +\infty)$, so f is strictly concave.

To verify that T_δ is satisfied for $\delta > 0$, we consider the expression $f''(\delta) - \frac{2}{\delta} \left(f'(\delta) - \frac{f(\delta)}{\delta} \right)$, which simplifies to

$$\frac{8(\delta+1)^{3/2} \text{ArcSinh}(\sqrt{\delta}) - \sqrt{\delta}(6\delta+5)}{4\delta^2(\delta+1)^{3/2}}.$$

The denominator of this expression is positive so we focus on the numerator, which we define to be $k(\delta)$. We have that $k(0) = 0$, so we will be able to conclude that k is non-negative if we can show that it is non-decreasing. Note that this k is not concave, so we cannot follow the method of the previous example. Rather, we calculate

$$k'(\delta) = \frac{3}{2\sqrt{\delta}} - 5\sqrt{\delta} + 12\sqrt{\delta+1} \log(\sqrt{\delta} + \sqrt{\delta+1}).$$

We will seek to demonstrate $k'(\delta) \geq 0$ by showing $k'(\delta) - 3/2\sqrt{\delta} \geq 0$. The derivative of $k'(\delta) - 3/2\sqrt{\delta}$ is

$$\frac{7}{2\sqrt{\delta}} + \frac{6 \text{ArcSinh}(\sqrt{\delta})}{\sqrt{\delta+1}},$$

which is clearly non-negative, and so T_δ is satisfied for $\delta > 0$. \diamond

It is natural to wonder whether T_δ is really needed in Theorem 2. Next, we give an example, where all conditions of Theorem 2 hold, except for T_δ , and the conclusion of Theorem 2 does *not* hold.

Example 8 For $\epsilon > 0$, let

$$f(w) := \begin{cases} \sqrt{w-1} - \sqrt{\epsilon} + \frac{1+\epsilon}{2\sqrt{\epsilon}}, & w \geq 1 + \epsilon; \\ \frac{1}{2\sqrt{\epsilon}}w, & w \leq 1 + \epsilon. \end{cases}$$

This function f , solid in Figure 2, has $f(0) = 0$, is differentiable, increasing and concave on $[0, +\infty)$ and is twice differentiable for $w > 1$.

Now, let $\delta = 1 + \epsilon + \phi$, for $\phi > 0$. For $\epsilon = 1/10$ and $\phi = 1/100$, $f''(\delta) - \frac{2}{\delta} \left(f'(\delta) - \frac{f(\delta)}{\delta} \right) \approx -6.7$, so our condition T_δ is *not* satisfied. In fact, a few calculations reveal that the associated cubic g , dotted in Figure 2, is *convex and decreasing* for $0 < w < \epsilon$. The issue is that f has too much negative curvature at δ to be concave on $[0, \delta]$ and have $f(0) = 0$. Note that by Lemma 5, we can add a small positive multiple of \sqrt{w} to f to get an example that is strictly concave and not differentiable at 0. \diamond

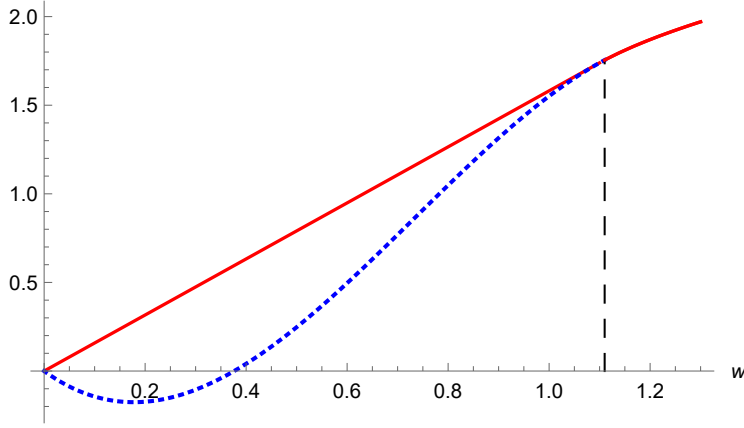


Fig. 2: g is convex and decreasing near 0

2 Lower bound for roots

For root functions, applying our general construction, direct calculation gives us the coefficients of $g(w) := Aw^3 + Bw^2 + Cw$:

$$\begin{aligned} A &= \delta^{p-3}(p^2 - 3p + 2)/2, \\ B &= -\delta^{p-2}(p^2 - 4p + 3), \\ C &= \delta^{p-1}(p^2 - 5p + 6)/2. \end{aligned}$$

For use in global optimization, we want control over the relationship between $f(w)$ and $g(w)$. We believe that $g(w) \leq f(w)$ on $[0, \delta]$ for all root functions f . For now, we can only establish this for $f(w) := w^p$, with $p := 1/q$ for *integer* $q \geq 2$. The case of $q = 2$ was established in [10,11] via a much easier argument (see the proof of Part 5 of Theorem 1 in the Appendix of [10]).

Theorem 9 For $f(w) := w^p$, with $p = 1/q$ for *integer* $q \geq 2$, we have $g(w) \leq f(w)$ for all $w \in [0, +\infty)$

Proof Clearly we can confine our attention to $[0, \delta]$. Our strategy is to express $f - g$ as the product of positive factors. It is convenient to make several substitutions before we factor. Starting with

$$(f - g)(w) = w^p - \frac{\delta^{p-3}}{2}(p^2 - 3p + 2)w^3 + \delta^{p-2}(p^2 - 4p + 3)w^2 - \frac{\delta^{p-1}}{2}(p^2 - 5p + 6)w,$$

for $0 \leq w \leq \delta$, we introduce the change the variables $t := w^p$, $q := 1/p$ and $L := \delta^p$ to arrive at

$$t - \frac{1}{2L^{3q-1}} \left(\frac{1}{q^2} - \frac{3}{q} + 2 \right) t^{3q} + \frac{1}{L^{2q-1}} \left(\frac{1}{q^2} - \frac{4}{q} + 3 \right) t^{2q} - \frac{1}{2L^{q-1}} \left(\frac{1}{q^2} - \frac{5}{q} + 6 \right) t^q,$$

for $0 \leq t \leq L$.

We begin factoring by removing a positive monomial,

$$= \frac{t}{2q^2 L^{3q-1}} \left(2q^2 L^{3q-1} - (6q^2 - 5q + 1)L^{2q} t^{q-1} \right)$$

$$+(6q^2 - 8q + 2)L^q t^{2q-1} - (2q^2 - 3q + 1)t^{3q-1} \Big),$$

so we can restrict our focus to the expression on the right, which we further simplify by making one last series of substitutions:

$$\begin{aligned} a &= 2q^2, \\ b &= 6q^2 - 5q + 1, \\ c &= 6q^2 - 8q + 2, \\ d &= 2q^2 - 3q + 1. \end{aligned}$$

We claim this last expression,

$$aL^{3q-1} - bL^{2q}t^{q-1} + cL^q t^{2q-1} - dt^{3q-1}, \quad (P_q)$$

factors into $Q_q(L-t)^3$, where Q_q is a polynomial in L and t . Because $0 \leq t \leq L$, $(L-t)^3$ is positive. With the Lemmas 12 and 13 in the Appendix, we show that Q_q is positive for integer $q \geq 2$, implying that $g(w) \leq f(w)$ for $w \in [0, \delta]$ as desired. \square

3 Better bound

We return, temporarily, to our general setting, where we are given a function f defined over the interval $[0, +\infty)$ having the following properties: $f(0) = 0$, f is increasing and concave on $[0, +\infty)$, $f'(w)$ and $f''(w)$ are defined on all of $(0, +\infty)$, but $f'(0)$ is undefined.

A natural and simple lower bound on f is to choose $\lambda > 0$, and define the *shifted* f as $h(w) := f(w + \lambda) - f(\lambda)$. It is easy to see that

$$h(w) := f(w + \lambda) - f(\lambda) \leq f(w),$$

because f is concave and non-negative at 0, which implies that f is subadditive on $[0, +\infty)$.

On the interval $[0, \delta]$, we wish to compare this h (the shifted f) to our smoothing g . But g is defined based on a choice of δ and h is defined based on a choice of λ , a fair comparison is achieved by making these choices so that the derivative at 0 is the same. In this way, both smoothings of f have the same numerical properties: they both have the same maximum derivative (maximized at zero where f' blows up).

At $w = 0$, the first derivative of g is

$$g'(0) = 3f(\delta)/\delta - 2f'(\delta) + \delta f''(\delta)/2.$$

We have that

$$h'(0) = f'(\lambda).$$

For each $\delta > 0$, there is a $\lambda > 0$ so that $g'(0) = h'(0)$. Now, suppose that f' is decreasing on $[0, +\infty)$. Then $(f')^{-1}$ exists, and

$$\hat{\lambda} := (f')^{-1} (3f(\delta)/\delta - 2f'(\delta) + \delta f''(\delta)/2)$$

is the value of λ for which $g'(0) = h'(0)$.

So, in general, we want to check that for each $\delta > 0$,

$$f(w + \hat{\lambda}) - f(\hat{\lambda}) \leq g(w), \quad (*)$$

for all $w \in (0, \delta)$. To go further, we now confine our attention, once again, to root functions.

Already, [10, 11] established this for the square-root function, though their proof has a certain weakness (see the proof of Proposition 3 in the Appendix of [10]), relying on some numerics, which our proof does not suffer from. Our goal is to establish this property for all root functions. This seems to be quite difficult, and so we set our focus now on root functions of the form $f(w) := w^p$, with $p := 1/q$ for integer $q \geq 2$. We have a substantial partial result, which as a by product provides an air-tight proof of the previous result of [10, 11] for $q = 2$.

Theorem 10 *For root functions of the form $f(w) := w^p$, with $p := 1/q$, (*) holds for integers $2 \leq q \leq 10,000$.*

Proof The function $(g - h)(w)$, which we wish to prove is non-negative on the interval $[0, \delta]$, is

$$\frac{\delta^{p-3}}{2}(p^2 - 3p + 2)w^3 - \delta^{p-2}(p^2 - 4p + 3)w^2 + \frac{\delta^{p-1}}{2}(p^2 - 5p + 6)w - (w + \hat{\lambda})^p + \hat{\lambda}^p,$$

where the shift constant $\hat{\lambda}$ for which $h'(0) = g'(0)$ is

$$\hat{\lambda} = (f')^{-1}(g'(0)) = \delta \left(\frac{p^2 - 5p + 6}{2p} \right)^{\frac{1}{p-1}}.$$

With a few substitutions, we simplify the function and express it in polynomial form. For the first substitution, set $q := 1/p$, $\gamma := \delta^{1/q}$, and $t := \frac{w}{\gamma}$. We obtain a function of t over $[0, 1]$ that has γ as a factor:

$$(g - h)_t(t) = \gamma \left[\frac{2q^2 - 3q + 1}{2q^2} t^3 + \frac{-6q^2 + 8q - 2}{2q^2} t^2 + \frac{6q^2 - 5q + 1}{2q^2} t - \left(\left(\frac{2q}{6q^2 - 5q + 1} \right)^{\frac{q}{q-1}} + t \right)^{1/q} + \left(\frac{2q}{6q^2 - 5q + 1} \right)^{\frac{1}{q-1}} \right].$$

Next, we set $Q := \left(\frac{2q}{6q^2 - 5q + 1} \right)^{\frac{1}{q-1}}$ and $u := (t + Q^q)^{1/q}$ (so $t \rightarrow u^q - Q^q$). The resulting polynomial in u is

$$(g - h)_u(u) = \frac{\gamma}{2q^2} \left[(2q^2 - 3q + 1)(u^q - Q^q)^3 + (-6q^2 + 8q - 2)(u^q - Q^q)^2 + (6q^2 - 5q + 1)(u^q - Q^q) + 2q^2Q - 2q^2u \right],$$

for $Q \leq u \leq (1 + Q^q)^{1/q}$. Since $\gamma > 0$, our task is reduced to proving that the second factor,

$$K_u(u) := d(u^q - Q^q)^3 - c(u^q - Q^q)^2 + b(u^q - Q^q) - a(u - Q),$$

where

$$a := 2q^2,$$

$$\begin{aligned} b &:= 6q^2 - 5q + 1, \\ c &:= 6q^2 - 8q + 2, \text{ and} \\ d &:= 2q^2 - 3q + 1, \end{aligned}$$

is non-negative for $Q \leq u \leq (1 + Q^q)^{1/q}$.

It is obvious that K_u has a root at Q . In fact, K_u has a double root at Q , which we can verify by showing that the first derivative of K_u ,

$$K'_u(u) = 3dq(u^q - Q^q)^2 u^{q-1} - 2cq(u^q - Q^q)u^{q-1} + bqu^{q-1} - a,$$

also has a root at Q . This is easily accomplished by noticing that

$$bqu^{q-1} = bq \left(\left(\frac{2q}{6q^2 - 5q + 1} \right)^{\frac{1}{q-1}} \right)^{q-1} = 2q^2 = a.$$

By construction of g and h ,

$$(g - h)_u((1 + Q^q)^{1/q}) = (g - h)(\delta) = (f - h)(\delta) > 0,$$

which means that $K_u((1 + Q^q)^{1/q}) > 0$. In order to prove that $K_u(u) \geq 0$ for $u \in (Q, (1 + Q^q)^{1/q})$, it suffices to show that there are no roots in the interval $(Q, (1 + Q^q)^{1/q})$. In fact, we prove that the only root in the interval $(0, (1 + Q^q)^{1/q}) \supseteq (Q, (1 + Q^q)^{1/q})$ is the double root at Q .

Using a known technique (e.g., see [19]), we apply the Möbius transformation

$$K_u \left(\frac{(1 + Q^q)^{1/q}}{v + 1} \right)$$

to express K_u , $u \in (0, (1 + Q^q)^{1/q})$, as a rational function in v over the interval $(0, \infty)$. Note that when $v = 0$, $K_u \left(\frac{(1 + Q^q)^{1/q}}{v + 1} \right) = K_u \left((1 + Q^q)^{1/q} \right)$, and as $v \rightarrow \infty$, $K_u \left(\frac{(1 + Q^q)^{1/q}}{v + 1} \right) \rightarrow K_u(0)$.

Next, we calculate expressions for the coefficients of the polynomial

$$K_v(v) := (v + 1)^{3q} K_u \left(\frac{\beta}{v + 1} \right),$$

where $\beta := (1 + Q^q)^{1/q}$, and the domain is $(0, \infty)$.

Expanding the binomials in u^q and Q^q and multiplying by $(v + 1)^{3q}$, we have

$$\begin{aligned} K_v(v) &= (aQ - bQ^q - cQ^{2q} - dQ^{3q})(v + 1)^{3q} - a\beta(v + 1)^{3q-1} \\ &\quad + (3d\beta^q Q^{2q} + 2c\beta^q Q^q + b\beta^q)(v + 1)^{2q} - (3d\beta^{2q} Q^q + c\beta^{2q})(v + 1)^q + d\beta^{3q}. \end{aligned}$$

Expanding binomials and collecting like terms, we find that

$$\begin{aligned} K_v(v) &= V + W + X + Y + Z \\ &\quad + \sum_{i=1}^q \left[\binom{q}{q-i} W + \binom{2q}{2q-i} X + \binom{3q-1}{3q-1-i} Y + \binom{3q}{3q-i} Z \right] v^i \\ &\quad + \sum_{i=q+1}^{2q} \left[\binom{2q}{2q-i} X + \binom{3q-1}{3q-1-i} Y + \binom{3q}{3q-i} Z \right] v^i \end{aligned}$$

$$+ \sum_{i=2q+1}^{3q-1} \left[\binom{3q-1}{3q-1-i} Y + \binom{3q}{3q-1} Z \right] v^i + Z v^{3q},$$

where

$$\begin{aligned} V &:= d\beta^{3q}, \\ W &:= -3d\beta^{2q}Q^q - c\beta^{2q}, \\ X &:= 3d\beta^qQ^{2q} + 2c\beta^qQ^q + b\beta^q, \\ Y &:= -a\beta, \text{ and} \\ Z &:= -dQ^{3q} - cQ^{2q} - bQ^q + aQ. \end{aligned}$$

Armed with these expressions for the coefficients of the polynomials $K_v(v)$, we verified (with **Mathematica**) that for integers $2 \leq q \leq 10,000$, there are exactly two sign changes in each coefficient sequence. By Descartes' Rule of Signs, we conclude that there are at most two positive roots of $K_v(v)$ (for these values of q), and therefore at most two roots of $K_u(u)$ in the interval $(0, (1+Q^q)^{1/q})$ (the double root at Q). \square

Our proof technique can work for any *fixed* integer $q \geq 2$. In carrying out the technique, there is some computational burden for which we employ **Mathematica**. We only carried this out for integers $2 \leq q \leq 10,000$, but in principle we could go further. It is important to point out that the calculations were done exactly and only truncated to finite precision at the end.

The remaining challenge is to make a proof for all integers $q \geq 2$. But the coefficients of $K_u\left(\frac{(1+Q^q)^{1/q}}{v+1}\right)$ are rather complicated for general q , so it is difficult to analyze their signs in general.

4 Average performance for roots

On $[\delta, +\infty)$, g coincides with f by definition (we are assuming that $f'(\delta)$ and $f''(\delta)$ are defined so that g is well defined), while h strictly under-estimates f for increasing concave functions f for which $f(\delta) > 0$. So it becomes interesting to examine the performance of g and h near 0, that is on the interval $[0, \delta]$. Here, we focus on average relative performance:

$$\frac{1}{\delta} \int_0^\delta \frac{g(w)}{f(w)} dw, \quad \frac{1}{\delta} \int_0^\delta \frac{h(w)}{f(w)} dw,$$

where we are further assuming that $f(0) = 0$ and f is increasing. In what follows, we compare these performance measures for root functions.

Theorem 11 For $f(w) = w^p$, $0 < p < 1$, and λ chosen as a function of $\delta > 0$ so that $g'(0) = h'(0)$, we have that

$$\frac{1}{\delta} \int_0^\delta \frac{g(w)}{f(w)} dw = \frac{3}{4-p},$$

notably independent of δ , and also

$$\frac{1}{\delta} \int_0^\delta \frac{h(w)}{f(w)} dw$$

is independent of the choice of δ .

Proof We apply the change of variable $w \rightarrow \delta v$ to rewrite each expression without δ . For the first integral, letting $a := \frac{1}{2}(p^2 - 3p + 2)$, $b := p^2 - 4p + 3$, and $c := \frac{1}{2}(p^2 - 5p + 6)$, we have

$$\begin{aligned} \frac{1}{\delta} \int_0^\delta \frac{g(w)}{f(w)} dw &= \frac{1}{\delta} \int_0^\delta \frac{\delta^{p-3}aw^3 - \delta^{p-2}bw^2 + \delta^{p-1}cw}{w^p} dw \\ &= \int_0^1 (av^{3-p} - bv^{2-p} + cv^{1-p}) dv. \\ &= \frac{a}{4-p} - \frac{b}{3-p} + \frac{c}{2-p} = \frac{3}{4-p}. \end{aligned}$$

Letting $P := \left(\frac{p^2-5p+6}{2p}\right)^{\frac{1}{p-1}}$ in the second integral, the change of variable produces

$$\begin{aligned} \frac{1}{\delta} \int_0^\delta \frac{h(w)}{f(w)} dw &= \frac{1}{\delta} \int_0^\delta \frac{(w + \delta P)^p - (\delta P)^p}{w^p} dw \\ &= \int_0^1 \frac{(v + P)^p - P^p}{v^p} dv, \end{aligned}$$

and again δ disappears from the expression. \square

We note that $\frac{3}{4-p}$ is increasing in p , and so its infimum on $(0, 1)$ is $\frac{3}{4}$ at $p = 0$. Additionally, we note that there is no closed-form expression for the last integration of the proof, though it can be expressed in terms of an evaluation of a Gaussian/ordinary hypergeometric function ${}_2F_1$ (see [2]). Specifically

$$\left(\frac{p^2 - 5p + 6}{2p}\right)^{\frac{p}{p-1}} \left(\frac{-1 + {}_2F_1(1-p, -p; 2-p; -1/p)}{1-p}\right).$$

In the key special case of $p = 1/2$, we do get the closed-form expression

$$\frac{8}{15} \left(-1 + \frac{3615 + 16\sqrt{241} \operatorname{ArcSinh}\left(\frac{15}{4}\right)}{120\sqrt{241}}\right) \approx 0.646125$$

(where $\operatorname{ArcSinh}(x) = \ln(x + \sqrt{x^2 + 1})$), which is significantly less than $\frac{3}{4-p} \Big|_{p=\frac{1}{2}} = \frac{6}{7} \approx 0.857143$.

In Figure 3 we have plotted the two performance measures, varying p on $(0, 1)$; Theorem 11 allows us to do this without separate curves for different δ . We can readily see that g outperforms h bigly, with the performance gap being most extreme as $p \rightarrow 0$, and decreasing in p on $(0, 1)$.

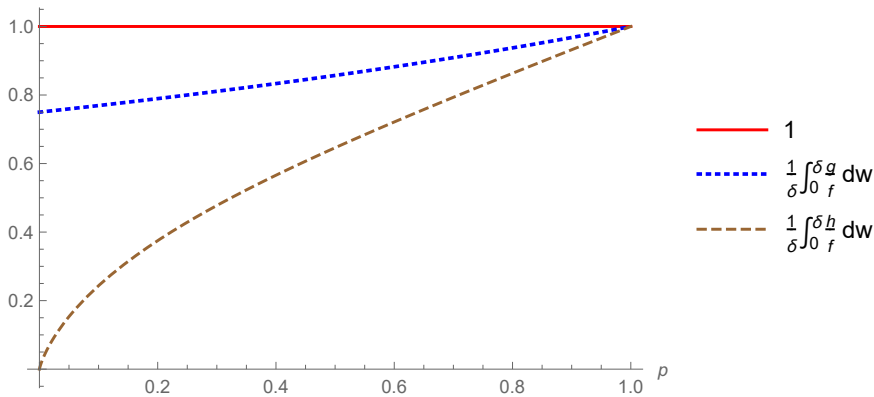


Fig. 3: Average relative performance on $[0, \delta]$ as a function of p
 $(f(w) := w^p, 0 < p < 1)$

5 Alternatives, software, extended use, and ongoing work

5.1 Alternatives

We do not mean to imply that our smoothing ideas are the only viable or even preferred way to handle all instances of the functions to which our ideas apply. For example, there is the possibility to take a function $f(w)$ and replace it with a new variable y and the constraint $f^{-1}(y) = w$. For example, $f(w) := w^p$, with $0 < p < 1$, can be replaced with y and the constraint $w = y^{\frac{1}{p}}$, which is now smooth at $w = 0$. But there is the computational cost of including an additional non-linear equation in a model. In fact, this could turn an unconstrained model into a constrained model. For other functions, we may not have a nice expression for the inverse readily available. Even when we do, there can be other issues to consider. Taking again $f(w) := w^p$, with $0 < p < 1$, suppose that we have $\psi : \mathbb{R}^m \rightarrow \mathbb{R}_+$ and $\phi : \mathbb{R}^n \rightarrow \mathbb{R}$. Now suppose that we have a model with the constraint $f(\psi(y)) \geq \phi(x)$. Of course y and x may be involved in other constraints as well. Now, suppose further that the range of ϕ on the feasible region is $(-\infty, +\infty)$. There could then be a difficulty in trying to work with $\psi(y) \geq f^{-1}(\phi(x))$, which we could repair by instead working with $\psi(y) \geq f^{-1}(\phi_+(x))$, where $\phi_+(x) := \max\{\phi(x), 0\}$. But this means working now with the piecewise-defined function ϕ_+ , which can involve a lot of pieces (e.g., consider the univariate $\phi(x) := \sin(x)$).

In the end, we do not see our technique as a panacea, but rather as a viable method with nice properties that modelers and solvers should have in their bags.

5.2 Software

In the context of the square-root smoothing of [10,11], a new and exciting experimental (“ α ”) feature was developed for SCIP Version 3.2 (see [15]) to handle univariate piecewise functions that are user-certified (through AMPL suffixes) as being globally convex or concave. At this writing, SCIP is the only global solver

that can accommodate such functions. Such a feature is extremely useful for taking advantage of the results that we present here, because our smoothings (like those of [10,11]) are piecewise-defined, and so the user must identify global concavity to the solver. This is accomplished through the new SCIP operator type `SCIP_EXPR_USER`. A bit of detail about this feature, from [15], is enlightening:

“Currently, the following callbacks can or have to be provided: computing the value, gradient, and Hessian of a user-function, given values (numbers or intervals) for all arguments of the function; indicating convexity/concavity based on bounds and convexity information of the arguments; tighten bounds on the arguments of the function when bounds on the function itself are given; estimating the function from below or above by a linear function in the arguments; copy and free the function data. Currently, this feature is meant for low-dimensional (few arguments) functions that are fast to evaluate and for which bound propagation and/or convexification methods are available that provide a performance improvement over the existing expression framework.”

5.3 Extended use

Our techniques have broader applicability than to functions that are purely concave (or symmetrically, convex). In general, given a univariate piecewise-defined function that is concave or convex on each piece, and possibly non-differentiable at each breakpoint, we can seek to find a smoothing that closely mimics and approximates the function. It is not at all clear how to accommodate such functions in global-optimization software like SCIP; because such functions are not, in general, *globally* concave or convex, they cannot be correctly handled with the new SCIP feature (see §5.2). Still, such functions and their smoothings can be useful within the common paradigm of seeking (good) local optima for non-linear-optimization formulations.

For example, for $0 < p < 1$, consider the function

$$f(w) := \begin{cases} w^p, & w \geq 0; \\ -(-w)^p, & w \leq 0. \end{cases}$$

This function is continuous, increasing, convex on $(-\infty, 0]$, concave on $[0, +\infty)$ and of course not differentiable at 0. We would like to replace it with a function that has all of these properties but is somewhat smooth at 0. If we apply our smoothing to f separately, for $w \geq 0$ and for $w \leq 0$, we would arrive at a function of the form

$$g(w) := \begin{cases} w^p, & w \geq \delta; \\ Aw^3 + Bw^2 + Cw, & 0 \leq w \leq \delta; \\ Aw^3 - Bw^2 + Cw, & -\delta \leq w \leq 0; \\ -(-w)^p, & w \leq -\delta, \end{cases}$$

for appropriate A, B, C (see §1). It is easy to check that the resulting g is continuous, *differentiable at 0*, twice differentiable everywhere but at 0, increasing, convex on $(-\infty, 0]$, and concave on $[0, +\infty)$. In short, g mimics f very well, but is smoother. Moreover, for $p = 1/q$, with integer $q \geq 2$, g upper bounds f on $(-\infty, 0]$ and lower bounds f on $[0, +\infty)$.

Note that the obvious “double shift”

$$h(w) := \begin{cases} (w + \lambda)^p, & w > 0; \\ ?, & w = 0; \\ -(-w + \lambda)^p, & w < 0 \end{cases}$$

is not even continuous at 0.

Additionally, for $p = 1/q$, with integer $2 \leq q \leq 10,000$, in the sense of §3, g is a better upper bound on f than h on $(-\infty, 0]$, and g is a better lower bound on f than h on $[0, +\infty)$.

5.4 Ongoing work

To extend the applicability of our results, we are pursuing two directions:

- We would like to generalize Theorem 9 to all root functions w^p with $0 < p < 1$. A strategy that we are exploring is to try to make a similar proof to what we have, for the case in which p is rational, and then employ a continuity argument to establish the result for all real exponents.
- We would like to generalize Theorem 10 for all root functions w^p with $0 < p < 1$. For now, that seems like a rather ambitious goal, and what is more in sight is generalizing Theorem 10 for *all* integer $q \geq 2$. To do this we are trying to sharpen our arguments employing Descartes’ Rule of Signs, or, alternatively, to develop a sum-of-squares argument.

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Appendix

Lemma 12 The polynomial P_q as defined above for integer $q \geq 2$ can be expressed as $Q_q(L-t)^3$, where polynomial Q_q has the following $3q-3$ terms:

$$\begin{aligned} & \binom{i+2}{2} a L^{3q-4-i} t^i, \text{ for } i = 0, 1, \dots, q-2; \\ & \left[\binom{i+2}{2} a - \binom{i-q+3}{2} b \right] L^{3q-4-i} t^i, \text{ for } i = q-1, q, \dots, 2q-2; \\ & \left[\binom{i+2}{2} a - \binom{i-q+3}{2} b + \binom{i-2q+3}{2} c \right] L^{3q-4-i} t^i, \text{ for } i = 2q-1, 2q, \dots, 3q-4. \end{aligned}$$

Note that for $q = 2$, $2q-2 = 3q-4 = 2$, so there are no terms of the third type.

Proof We expand $Q_q(L-t)^3$ to see that it is equivalent to P_q , first for specific cases $q = 2, 3$ and 4, and finally for general $q \geq 5$. The following are easily verified:

$$\begin{aligned} & \underline{Q_q(L-t)^3 = P_q} \\ q = 2: & (8L^2 + 9Lt + 3t^2)(L-t)^3 = 8L^5 - 15L^4t + 10L^2t^3 - 3t^5; \\ q = 3: & (18L^5 + 54L^4t + 68L^3t^2 + 60L^2t^3 + 30Lt^4 + 10t^5)(L-t)^3 \\ & = 18L^8 - 40L^6t^2 + 32L^3t^5 - 10t^8; \\ q = 4: & (32L^8 + 96L^7t + 192L^6t^2 + 243L^5t^3 + 249L^4t^4 + 210L^3t^5 \\ & + 126L^2t^6 + 63Lt^7 + 21t^8)(L-t)^3 = 32L^{11} - 77L^8t^3 + 66L^4t^7 - 21t^{11}. \end{aligned}$$

Now considering general $q \geq 5$, most of the terms of $Q_q(L-t)^3$ cancel out due to the following equations:

$$\begin{aligned} & (-3) \binom{2}{2} + \binom{3}{2} = -3 + 3 = 0; \\ & (3) \binom{2}{2} + (-3) \binom{3}{2} + \binom{4}{2} = 3 - 9 + 6 = 0; \end{aligned}$$

and for $i \geq 3$,

$$(-1) \binom{i-1}{2} + (3) \binom{i}{2} + (-3) \binom{i+1}{2} + \binom{i+2}{2} = 0.$$

If the expression for the coefficient of t^j , $0 \leq j \leq 3q-1$, has more than one term involving a , b , or c , that variable (a , b , or c) has a coefficient of one of the forms above and cancels out. The only time the variable remains is when it has only a single term in the expression. The terms of $Q_q(L-t)^3 = Q_q(-t^3 + 3Lt^2 - 3L^2t + L^3)$ for $q \geq 5$ increasing in the degree j of t are as follows:

$$j = 0: \quad (aL^{3q-4}) \binom{L^3}{L^3} = aL^{3q-1}$$

$$\begin{aligned}
j = 1 &: (aL^{3q-4})(-3L^2t) + (3aL^{3q-5}t)(L^3) \\
&= (-3 + 3)aL^{3q-2}t \\
&= 0 \\
j = 2 &: (aL^{3q-4})(3Lt^2) + (3aL^{3q-5}t)(-3L^2t) + (6aL^{3q-6}t^2)(L^3) \\
&= (3 - 9 + 6)aL^{3q-3}t^2 \\
&= 0 \\
3 \leq j \leq q-2 &: \binom{j-1}{2}aL^{3q-1-j}t^{j-3}(-t^3) + \binom{j}{2}aL^{3q-2-j}t^{j-2}(3Lt^2) + \\
&\quad \binom{j+1}{2}aL^{3q-3-j}t^{j-1}(-3L^2t) + \binom{j+2}{2}aL^{3q-4-j}t^j(L^3) \\
&= \left[(-1)\binom{j-1}{2} + (3)\binom{j}{2} + (-3)\binom{j+1}{2} + \binom{j+2}{2} \right] aL^{3q-1-j}t^j \\
&= 0 \\
j = q-1 &: \binom{q-2}{2}aL^{2q}t^{q-4}(-t^3) + \binom{q-1}{2}aL^{2q-1}t^{q-3}(3Lt^2) + \\
&\quad \binom{q}{2}aL^{2q-2}t^{q-2}(-3L^2t) + \left[\binom{q+1}{2}a-b \right] L^{2q-3}t^{q-1}(L^3) \\
&= \left[(-1)\binom{q-2}{2} + (3)\binom{q-1}{2} + (-3)\binom{q}{2} + \binom{q+1}{2} \right] aL^{2q}t^{q-1} \\
&\quad - bL^{2q}t^{q-1} \\
&= -bL^{2q}t^{q-1} \\
j = q &: \binom{q-1}{2}aL^{2q-1}t^{q-3}(-t^3) + \binom{q}{2}aL^{2q-2}t^{q-2}(3Lt^2) + \\
&\quad \left[\binom{q+1}{2}a-b \right] L^{2q-3}t^{q-1}(-3L^2t) + \left[\binom{q+2}{2}a-3b \right] L^{2q-4}t^q(L^3) \\
&= \left[(-1)\binom{q-1}{2} + (3)\binom{q}{2} + (-3)\binom{q+1}{2} + \binom{q+2}{2} \right] aL^{2q-1}t^q \\
&\quad + (3-3)bL^{2q-1}t^q \\
&= 0 \\
j = q+1 &: \binom{q}{2}aL^{2q-2}t^{q-2}(-t^3) \\
&\quad + \left[\binom{q+1}{2}a-b \right] L^{2q-3}t^{q-1}(3Lt^2) \\
&\quad + \left[\binom{q+2}{2}a-3b \right] L^{2q-4}t^q(-3L^2t)
\end{aligned}$$

$$\begin{aligned}
& + \left[\binom{q+3}{2} a - 6b \right] L^{2q-5} t^{q+1} (L^3) \\
& = 0 \\
q+2 \leq j \leq 2q-2 : & \left[\binom{j-1}{2} a - \binom{j-q}{2} b \right] L^{3q-1-j} t^{j-3} (-t^3) \\
& + \left[\binom{j}{2} a - \binom{j-q+1}{2} b \right] L^{3q-2-j} t^{j-2} (3Lt^2) \\
& + \left[\binom{j+1}{2} a - \binom{j-q+2}{2} b \right] L^{3q-3-j} t^{j-1} (-3L^2t) \\
& + \left[\binom{j+2}{2} a - \binom{j-q+3}{2} b \right] L^{3q-4-j} t^j (L^3) \\
& = 0 \\
j = 2q-1 : & \left[\binom{2q-2}{2} a - \binom{q-1}{2} b \right] L^q t^{2q-4} (-t^3) \\
& + \left[\binom{2q-1}{2} a - \binom{q}{2} b \right] L^{q-1} t^{2q-3} (3Lt^2) \\
& + \left[\binom{2q}{2} a - \binom{q+1}{2} b \right] L^{q-2} t^{2q-2} (-3L^2t) \\
& + \left[\binom{2q+1}{2} a - \binom{q+2}{2} b + c \right] L^{q-3} t^{2q-1} (L^3) \\
& = cL^q t^{2q-1} \\
j = 2q : & \left[\binom{2q-1}{2} a - \binom{q}{2} b \right] L^{q-1} t^{2q-3} (-t^3) \\
& + \left[\binom{2q}{2} a - \binom{q+1}{2} b \right] L^{q-2} t^{2q-2} (3Lt^2) \\
& + \left[\binom{2q+1}{2} a - \binom{q+2}{2} b + c \right] L^{q-3} t^{2q-1} (-3L^2t) \\
& + \left[\binom{2q+2}{2} a - \binom{q+3}{2} b + 3c \right] L^{q-4} t^{2q} (L^3) \\
& = 0 \\
j = 2q+1 : & \left[\binom{2q}{2} a - \binom{q+1}{2} b \right] L^{q-2} t^{2q-2} (-t^3) \\
& + \left[\binom{2q+1}{2} a - \binom{q+2}{2} b + c \right] L^{q-3} t^{2q-1} (3Lt^2) \\
& + \left[\binom{2q+2}{2} a - \binom{q+3}{2} b + 3c \right] L^{q-4} t^{2q} (-3L^2t)
\end{aligned}$$

$$\begin{aligned}
& + \left[\binom{2q+3}{2}a - \binom{q+4}{2}b + 6c \right] L^{q-5}t^{2q+1} (L^3) \\
& = 0 \\
2q+2 \leq j \leq 3q-4 : & \left[\binom{j-1}{2}a - \binom{j-q}{2}b + \binom{j-2q}{2}c \right] L^{3q-1-j}t^{j-3} (-t^3) \\
& + \left[\binom{j}{2}a - \binom{j-q+1}{2}b + \binom{j-2q+1}{2}c \right] L^{3q-2-j}t^{j-2} (3Lt^2) \\
& + \left[\binom{j+1}{2}a - \binom{j-q+2}{2}b + \binom{j-2q+2}{2}c \right] L^{3q-3-j}t^{j-1} (-3L^2t) \\
& + \left[\binom{j+2}{2}a - \binom{j-q+3}{2}b + \binom{j-2q+3}{2}c \right] L^{3q-4-j}t^j (L^3) \\
& = 0
\end{aligned}$$

The cancellation pattern above fails for the last three terms. It is necessary to replace a , b , and c with the equivalent expressions involving q to verify each of the following.

$$\begin{aligned}
j = 3q-3 : & \left[\binom{3q-4}{2}a - \binom{2q-3}{2}b + \binom{q-3}{2}c \right] L^2t^{3q-6}(-t^3) \\
& + \left[\binom{3q-3}{2}a - \binom{2q-2}{2}b + \binom{q-2}{2}c \right] Lt^{3q-5}(3Lt^2) \\
& + \left[\binom{3q-2}{2}a - \binom{2q-1}{2}b + \binom{q-1}{2}c \right] t^{3q-4}(-3L^2t) \\
& = 0 \\
j = 3q-2 : & \left[\binom{3q-3}{2}a - \binom{2q-2}{2}b + \binom{q-2}{2}c \right] Lt^{3q-5}(-t^3) \\
& + \left[\binom{3q-2}{2}a - \binom{2q-1}{2}b + \binom{q-1}{2}c \right] t^{3q-4}(3Lt^2) \\
& = 0 \\
j = 3q-1 : & \left[\binom{3q-2}{2}a - \binom{2q-1}{2}b + \binom{q-1}{2}c \right] t^{3q-4}(-t^3) = -dt^{3q-1}
\end{aligned}$$

□

Lemma 13 The polynomial Q_q as defined in the previous lemma for integers $q \geq 2$ has all positive coefficients.

Proof We consider each of the three types of coefficients of Q_q separately. The first type of coefficients,

$$\binom{i+1}{2}2q^2, \text{ for } i = 1, 2, \dots, q-1,$$

are obviously all positive.

Coefficients of the second type have the form

$$\binom{i+1}{2}a - \binom{i-q+2}{2}b, \text{ for } i = q, q+1, \dots, 2q-1.$$

The real function $C_2(x) = \frac{1}{2}(x+1)(x)a - \frac{1}{2}(x-q+2)(x-q)b$, $x \in [q, 2q-1]$, has second derivative $C_2''(x) = -4q^2 + 5q - 1$, which is negative for $q > 1$. Therefore, C_2 is concave on the interval $[q, 2q-1]$. Evaluating C_2 at the ends of the interval, we find that $C_2(q) = q^4 + q^3 - 6q^2 + 5q - 1$ and $C_2(2q-1) = q^4 - \frac{5}{2}q^3 + 2q^2 - \frac{1}{2}q$, both of which are positive for $q > 1$. We conclude that C_2 is positive over the interval $[q, 2q-1]$, and all of the type-two coefficients are positive.

Finally, the third type of coefficients have the form

$$\binom{i+1}{2}a - \binom{i-q+2}{2}b + \binom{i-2q+2}{2}c, \text{ for } i = 2q, 2q+1, \dots, 3q-3.$$

As above, we consider the real extension of this function, $C_3(x) = \frac{1}{2}(x+1)(x)a - \frac{1}{2}(x-q+2)(x-q+1)b + \frac{1}{2}(x-2q+2)(x-2q+1)c$, $x \in [2q, 3q-3]$. The first derivative of this function, $C_3'(x) = (2q^2 - 3q + 1)x - (6q^3 - 12q^2 + \frac{15}{2}q - \frac{3}{2})$, is linear in x and has positive slope for $q > 1$. Furthermore, the x intercept of $C_3'(x)$ is $x = 3q - \frac{3}{2}$. This means that $C_3'(x) < 0$ for $x < 3q - \frac{3}{2}$. In particular, $C_3(x)$ is decreasing on the interval $[2q, 3q-3]$. The right end of this interval is $C_3(3q-3) = 2q^2 - 3q + 1$, which is positive for $q > 1$, and all of the type-three terms are positive. \square