In this note we will construct (cf. formulas (1)) an example of a non-negative, strictly increasing, continuously differentiable function  $d \colon [0, \infty) \to [0, \infty)$ , bounded from above by a convex function  $f \colon [0, \infty) \to [0, \infty)$ , f(0) = 0, such that the function d is not convex on any interval  $I \subseteq [0, \infty)$ . Such considerations are interesting from the point of view of [2, p. 167]. It is (implicitly) stated there, that if a decreasing function  $\tilde{d} \geqslant 0$  is bounded from above by a convex function  $\tilde{f}$  vanishing at some point b > 0, then the function  $\tilde{d}$  is convex on some interval arbitrary close to b. After considering the mappings

$$d(x) = \widetilde{d}(b-x), \ f(x) = \widetilde{f}(b-x) \quad (x \in [0,b]),$$

one sees that instead of decreasing function  $\widetilde{d}$ , we can consider increasing function d. We will use the following results

**Theorem 1.** There exists a continuous, bounded and nowhere differentiable function  $w \colon \mathbb{R} \to \mathbb{R}$ 

Example of such function can be found in [1, Example 8, p. 38].

**Theorem 2.** If the function g is convex in an interval (a,b), then g is continuous in (a,b). Moreover, g' exists except at most in a countable set and is monotone increasing.

The proof of above Theorem can be found in [3, Theorem 7.40, p. 120].

**Theorem 3.** Let  $g:(a,b) \to \mathbb{R}$  be monotone increasing. Then the function g has a measurable, non-negative derivative g' almost everywhere in (a,b).

For the proof of the above we refer to [3, Theorem 7.21, page 111].

Consider  $\alpha \geqslant 0$  and let  $w \colon \mathbb{R} \to [0,1]$  be a continuous, nowhere differentiable function. Define the functions  $d, f \colon [0, \infty) \to \mathbb{R}$  as follows

$$d(x) = \int_0^x s^{\alpha} w(s) \, ds \quad (x \ge 0),$$
  

$$f(x) = \int_0^x s^{\alpha} \, ds = \frac{x^{\alpha+1}}{\alpha+1} \quad (x \ge 0).$$
(1)

Remark 4. The function f is convex and f(0) = f'(0) = 0.

Remark 5. The following inequality holds true

$$0 \leqslant d(x) \leqslant f(x) \quad (x \geqslant 0)$$
.

*Proof.* Observe that

$$0 \leqslant d'(s) = s^{\alpha} w(s) \leqslant s^{\alpha} = f'(s) \quad (s > 0).$$

Integrating above inequality over the set [0, x] gives the claim.

**Proposition 6.** The function d is continuously differentiable and if  $\alpha > 1$  then d''(0) = 0 (1).

Repository with the most recent version of this document: https://github.com/vil02/nowhere\_convex here we consider d''(0) as the limit  $\lim_{h\to 0^+} \frac{d'(h)-d'(0)}{h}$ .

*Proof.* Observe that  $d'(x) = x^{\alpha}w(x)$   $(x \in [0, \infty))$ . Moreover, we have

$$\frac{d'(h) - d'(0)}{h} = \frac{h^{\alpha}w(\alpha)}{h} \xrightarrow[h \to 0^{+}]{} 0,$$

for all  $\alpha > 1$ .

**Proposition 7.** The function d' is not differentiable for x > 0.

*Proof.* Suppose the contrary and consider the quotient

$$\frac{d'(x+h) - d'(x)}{h} = \frac{(x+h)^{\alpha} w(x+h) - x^{\alpha} w(x)}{h} 
= \frac{(x+h)^{\alpha} w(x+h) - (x+h)^{\alpha} w(x) + (x+h)^{\alpha} w(x) - x^{\alpha} w(x)}{h} 
= (x+h)^{\alpha} \frac{w(x+h) - w(x)}{h} + w(x) \frac{(x+h)^{\alpha} - x^{\alpha}}{h}$$
(2)

By our assumption the quotient of the left hand side of (2) converges to d''(x) as  $h \to 0$ . By the continuity of the function w and and differentiability of the function  $(0, \infty) \ni s \longmapsto s^{\alpha} \in (0, \infty)$ , we get that the limit  $\lim_{h\to 0} \frac{u(x+h)-u(x)}{h}$  exists. Therefore the function w is differentiable at point x. Contradiction.

**Proposition 8.** The function d is strictly increasing.

*Proof.* Clearly  $d'(x) = x^{\alpha}w(x) \ge 0 \ (x \ge 0)$ , therefore

$$d(a) - d(b) = \int_{b}^{a} d'(s) \, \mathrm{d}s \geqslant 0 \quad (a \geqslant b \geqslant 0) \, .$$

Suppose that there exist some points  $a > b \ge 0$ , such that

$$0 = d(a) - d(b) = \int_{b}^{a} d'(s) ds.$$

Since  $d' \ge 0$ , we have that d'(s) = 0 for almost all  $s \in [a, b]$ . By the continuity of the function d', we have that d'(s) = 0 ( $s \in [a, b]$ ). Hence, the function d' is differentiable on the interval (a, b), which gives a contradiction (cf. Proposition 7).

**Proposition 9.** The function d is not convex on any of the intervals  $I \subseteq [0, \infty)$ .

*Proof.* Suppose that there exists an interval  $I \subseteq [0, \infty)$  such that the function  $d_{|I|}$  is convex. Theorem 2 implies that the function d' is monotone increasing. Therefore, by Theorem 2 the function d' is differentiable almost everywhere (with respect to Leagues measure) on I. This gives the contradiction together with Proposition 7.

Remark 10. Let the functions d and f be as above (cf. formula (1)) and let b > 0. Consider functions  $\widetilde{d}, \widetilde{f} : [0, b] \to [0, \infty)$  defined as follows:

$$\widetilde{d}(x) = d(b - x) \quad (x \in [0, b]),$$

$$\widetilde{f}(x) = f(b - x) \quad (x \in [0, b]).$$

Then

- $0 \leqslant \widetilde{d}(x) \leqslant \widetilde{f}(x)$  for all  $x \in [0, b]$  (cf. Remark 5),
- the function  $\widetilde{f}$  is convex on the interval [0,b] and  $\widetilde{f}(0)=\widetilde{f}'(b)=0$  (cf. Remark 4),
- the function  $\widetilde{d}$  is of the class  $C^1$  on [0,b] (cf. Proposition 6),
- the function  $\widetilde{d}$  is strictly decreasing on the interval [0, b] (cf. Proposition 8),
- the function  $\widetilde{d}$  is not convex on any interval  $I \subseteq [0,b]$  (cf. Proposition 9).

## References

- [1] John M. H. Olmsted Bernard R. Gelbaum. *Counterexamples in Analysis*. Mathesis series. Holden-Day, 1964.
- [2] Steven Levandosky. Stability and instability of fourth-order solitary waves. *Journal of Dynamics and Differential Equations*, 10(1):151–188, Jan 1998.
- [3] Antoni Zygmund Richard L. Wheeden. *Measure and Integral: An Introduction to Real Analysis*. Chapman & Hall/CRC Pure and Applied Mathematics. Taylor & Francis, 1977.