

Product of Distributions Applied to Discrete Differential Geometry

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Abstract

A method for dealing with the product of step discontinuous and delta functions is proposed. A standard method for applying the above defined product of distributions to polyhedron vertices is analysed and the method is applied to a special case where the well known defect angle formula, for the discrete curvature of polyhedra, is derived using the tools of tensor calculus.

Key Words: distribution theory, product of distributions, discrete differential geometry.

1 Introduction

Products of distributions are quite common in several fields of both mathematics and physics. Examples arise naturally in quantum field theory, gravitation and in partial differential equations (e.g shock wave solutions in hydrodynamics) see [1]. An important issue, related to product of distributions, is the fact that the product, in the general case, is not well defined in D' . This issue is known as the Schwartz impossibility result (see [1] §1.3). In the Schwartz classical theory, only the product between a smooth function and a distribution is well defined. Historically, products of distributions are addressed by means of algebras of generalised functions developed initially by J. F. Colombeau (see [1] and [2]).

Discrete differential geometry is a rather new field of mathematics which borrows concepts and ideas from both differential geometry and discrete mathematics. Main applications are concerned with the discrete version of several classical concepts of differential geometry such as discrete curvature, minimal surfaces, geodesics coordinates, minimal paths, surfaces of constant curvature, curvature line parametrisation and the discrete version of continuous functionals (see [3]). At the moment, discrete differential geometry uses many tools of discrete mathematics while the classical tools of differential geometry (e.g. tensors and coordinate free exterior calculus) are difficult to be applied. This leads to an ambiguous definition of the various operators (see [4]) which are instead well defined in the continuous counterpart of the theory.

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In this paper, we propose a method for evaluating the product of step discontinuous functions and Dirac delta functions, related each other by an integrable function. Moreover, the method is applied to a special class of non differentiable varieties for which, the classical idea of curvature, together with all tools of differential geometry, needs to be redefined in terms of distribution functions. In particular, the class of varieties analysed is the one composed of a collection of several Riemannian varieties glued in such a way the final surface is not differentiable on the resulting edges and vertices. In this case, it is possible to show that vertices and edges carry a concentrated discrete curvature which gives a contribution to the total curvature of the surface, contribution that has to be taken into account in order for the Gauss-Bonnet theorem to work.

For vertices, an important result was already known since the time of Descartes which proved, in the first half of the 17th century, its defect angle theorem for polyhedra. That idea, using the modern concept of curvature and applied to the class of surfaces defined above, can be stated by saying that the discrete total curvature of a vertex is equal to 2π minus the sum of the angles between edges.

For edges, using the Gauss-Bonnet theorem, it is easy to see that the discrete curvature carried by an edge L_{ij} is given by:

$$k_{L_{ij}} = \int_{L_{ij}} (k_{g_i} + k_{g_j}) ds \quad (1)$$

where k_{g_i} and k_{g_j} are the geodesic curvatures, evaluated on the edge L_{ij} , of the two faces S_i and S_j for which L_{ij} is the boundary. If the surface is differentiable on L_{ij} , then k_{g_i} and k_{g_j} are opposite and the integral vanishes. If the surface is not differentiable, the integral (1) gives in general a finite result which corresponds to the discrete curvature concentrated on L_{ij} and $(k_{g_i} + k_{g_j})$ is the discrete curvature for unit length of the surface on L_{ij} .

This kind of surfaces, characterised by a step discontinuous metric, are typical of problems ranging from theoretical physics up to computer graphics, where the usual way to proceed is to break down the problem and to define boundary conditions (with conserved quantities) in order to keep the whole problem definition consistent (see [5]) or to use methods of discrete mathematics to define the relevant operators (see [4]). The approach proposed in this paper is to use a more direct method derived from the classical differential geometry.

In Paragraphs 2 and 3, we derive a method for evaluating products of step discontinuous and Dirac delta functions of the type

$$f(g_1(x_1), \dots, g_n(x_n))\delta(x_1, \dots, x_n) \quad (2)$$

where $g_i(x_i)$ are step discontinuous functions and f is a locally integrable function. This result is partially known in the literature (compare with [6]).

In Paragraphs 4 and 5, we use the product of step discontinuous and Dirac delta functions, mentioned above, to evaluate the discrete curvature of a polyhedron vertex. In order to do that, we define the step discontinuous metric of polyhedron vertices and we evaluate their Riemann tensors by applying the classical rules of the differential geometry but taking the derivatives in D' . By using this approach, the final result is, as expected, the defect angle formula for the total curvature of a polyhedron vertex.

2 Product of steps and delta functions

Proposition 1. Let $g(x)$ be a function defined as follows:

$$g(x) = \begin{cases} a & \text{for } x < 0 \\ b & \text{for } x > 0 \end{cases} \quad (3)$$

with $a, b \in \mathbb{R}$, and let $f(x)$ be any function locally integrable in $A \supseteq [a, b]$ (or $[b, a]$ if $b < a$). Also let $(b - a)\delta(x)$ be the derivative of $g(x)$. Then:

$$f(g(x))\delta(x) = \frac{1}{b - a} \left(\int_a^b f(x)dx \right) \delta(x) \quad (4)$$

where the above product has to be intended as:

$$f(g(x))\delta(x) = \frac{1}{b - a} \lim_{n \rightarrow \infty} f(g_n(x))g'_n(x) \quad (5)$$

for any sequence g_n such that:

$$\begin{aligned} 1) & g_n(x) \in C^1 \quad \forall n \in \mathbb{N} \\ 2) & \lim_{n \rightarrow \infty} g_n(x) = g(x) \\ 3) & \lim_{x \rightarrow -\infty} g_n(x) = a \quad \forall n \in \mathbb{N} \\ 4) & \lim_{x \rightarrow +\infty} g_n(x) = b \quad \forall n \in \mathbb{N} \\ 5) & g_n(x) \text{ is monotonic } \forall n \in \mathbb{N} \end{aligned} \quad (6)$$

Moreover, we choose each $g_n(x)$ such that, if $g_n(x)$ is constant in any $]\alpha, \beta[$ and equal to k , then $f(x)$ is continuous in k .

Proof. The proof is given for $a < b$ only, changes to the proof, for the case $b < a$, are trivial. We note immediately that, given the (6), the $g_n(x)$ are bounded and converge to $g(x)$. For the dominated convergence theorem, $g_n(x)$ converges in L^1_{loc} and therefore in D' . Also g'_n converges to $(b - a)\delta(x)$ in D' .

First, we prove two useful equations. For any $f \in L^1_{loc}(A)$, for any $g_n(x)$ having the characteristics (6) and given any $\alpha, \beta \in \mathbb{R}$ we have:

$$\int_{\alpha}^{\beta} f(g_n(x))g'_n(x)dx = \int_{\alpha}^{\beta} \frac{d}{dx} F(g_n(x))dx = F(g_n(\beta)) - F(g_n(\alpha)) \quad (7)$$

where $F(x)$ is the primitive of $f(x)$.

Now, $\lim_{\alpha \rightarrow -\infty} g_n(\alpha) = a$ and $\lim_{\beta \rightarrow +\infty} g_n(\beta) = b$ and therefore we have:

$$\int_{-\infty}^{+\infty} f(g_n(x))g'_n(x)dx = \int_a^b f(x)dx \quad (8)$$

The (8) does not depend from the function $g_n(x)$ since it depends only on $f(x)$, a and b .

Also, let $[\alpha, \beta]$ be any interval. Given the (6), $g'_n \geq 0$. We write $f(x) = f_+(x) - f_-(x)$ as the sum of its positive and negative part. Note that

$f_+(x)$ and $f_-(x)$ are locally integrable on A . We have:

$$\begin{aligned}
\int_{\alpha}^{\beta} |f(g_n(x))g'_n(x)|dx &= \int_{\alpha}^{\beta} f_+(g_n(x))g'_n(x)dx + \int_{\alpha}^{\beta} f_-(g_n(x))g'_n(x)dx \\
&= \int_{g_n(\alpha)}^{g_n(\beta)} f_+(x)dx + \int_{g_n(\alpha)}^{g_n(\beta)} f_-(x)dx \\
&= \int_{g_n(\alpha)}^{g_n(\beta)} |f(x)|dx \\
&\leq \int_a^b |f(x)|dx = M > 0
\end{aligned} \tag{9}$$

Now we can prove the proposition. Let $\phi(x)$ be a test function, taking into account the (8) it is possible to write:

$$\begin{aligned}
&\left| \int_{-\infty}^{+\infty} f(g_n(x))g'_n(x)\phi(x)dx - \left(\int_a^b f(x)dx \right) \phi(0) \right| \\
&= \left| \int_{-\infty}^{+\infty} f(g_n(x))g'_n(x)[\phi(x) - \phi(0)]dx \right| \\
&\leq I_{m1} + I_{m2} + I_{m3}
\end{aligned} \tag{10}$$

where m is any positive integer and:

$$I_{m1} = \int_{-\infty}^{-1/m} |f(g_n(x))g'_n(x)| |\phi(x) - \phi(0)| dx \tag{11}$$

$$I_{m2} = \int_{-1/m}^{+1/m} |f(g_n(x))g'_n(x)| |\phi(x) - \phi(0)| dx \tag{12}$$

$$I_{m3} = \int_{+1/m}^{+\infty} |f(g_n(x))g'_n(x)| |\phi(x) - \phi(0)| dx \tag{13}$$

Since ϕ is a test function, it is continuous at $x = 0$. Given any $\epsilon > 0$, it is possible to find $\delta > 0$ such that, whenever $|x| < \delta$, $|\phi(x) - \phi(0)| < \epsilon$. So, given any $m > \frac{1}{\delta}$, if we choose any $n > m$, we have:

$$\begin{aligned}
I_{m2} &= \int_{-1/m}^{+1/m} |f(g_n(x))g'_n(x)| |\phi(x) - \phi(0)| dx \\
&\leq \epsilon \int_{-1/m}^{+1/m} |f(g_n(x))g'_n(x)| dx \leq M\epsilon
\end{aligned} \tag{14}$$

Where we have used the (9).

Now, ϕ is a continuous function with compact support S and therefore it is bounded. We can find $L > 0$ such that $|\phi(x) - \phi(0)| < L$. We have:

$$\begin{aligned}
I_{m1} &= \int_{-\infty}^{-1/m} |f(g_n(x))g'_n(x)| |\phi(x) - \phi(0)| dx \\
&\leq \int_S L dx \int_{-\infty}^{-1/m} |f(g_n(x))g'_n(x)| dx \\
&= N \int_a^{g_n(-1/m)} |f(x)| dx
\end{aligned} \tag{15}$$

where we have used the (9) and $N > 0$ is the integral of the constant L on S . Since $g_n(-1/m)$ converge to a and given the ϵ above, it is possible to find k such that, whenever $n > k$ then $I_{m1} < N\epsilon$. Applying the same argument to I_{m3} we find that, it is also possible to find k such that, whenever $n > k$ then $I_{m3} < N\epsilon$.

To conclude, given the (10) and given any $\epsilon > 0$, it is possible to find first m and then k such that, whenever we choose $n > k > m$ we have:

$$\left| \int_{-\infty}^{+\infty} f(g_n(x))g'_n(x)\phi(x)dx - \left(\int_a^b f(x)dx \right) \phi(0) \right| \leq (M + 2N)\epsilon \quad (16)$$

This proves that:

$$\lim_{n \rightarrow \infty} \int_{-\infty}^{+\infty} f(g_n(x))g'_n(x)\phi(x)dx = \left(\int_a^b f(x)dx \right) \phi(0) \quad (17)$$

Now, if we call $(b - a)f(g(x))\delta(x)$ the limit of the sequence of distributions $f(g_n(x))g'_n(x)$, the (17) proves the following:

- the limit exists
- the limit is a Dirac delta function
- the amplitude of the delta function is given by the (4) □

The above result is already present in the literature (compare with [6]). With respect of the theory developed in [6], in this paper, we have derived the (4) by means of a completely different approach, we require f to be integrable (in [6] f is required to be continuous) and we have generalised the equation to the multidimensional case (see next paragraph).

Note that, even in the case where $f(a) = f(b)$ and therefore there is no step in the discontinuity, proposition 1 is essential to evaluate the product of the discontinuity with a related delta function. For example, is easy to show that $sign^2(x)\delta(x) = \frac{1}{3}\delta(x)$.

We also note that the constrains (6) used to prove proposition 1 are too stringent and that, in practical calculations, it is possible to relax them (see appendix A.2).

We finish this paragraph with a general remark on product of distributions and the way they are addressed in this paper. Every time we define the product in a point x_0 , where the distributions are discontinuous, we always want the discontinuities to have each other structure related by a well known law (in this case, one to be the derivatives of the other) so that, if the structure of one distribution in x_0 , which is unknown to us, changes, the structure of all other distributions in the same point will change accordingly.

Since we never want to define the structures of the discontinuities, we are mostly interested in products of distributions, like the one of proposition 1, which works regardless their underlying structures. This is why in proposition 1 we define the product as the limit of some classes of sequences (i.e. structure) and we want this limit to be independent from it.

3 The multidimensional case

Proposition 2. *Let $g_1(x)$ and $g_2(y)$ be two functions defined as follows:*

$$g_1(x) = \begin{cases} a & \text{for } x < 0 \\ b & \text{for } x > 0 \end{cases} \quad (18)$$

$$g_2(y) = \begin{cases} c & \text{for } y < 0 \\ d & \text{for } y > 0 \end{cases} \quad (19)$$

with $a, b, c, d \in \mathbb{R}$ and let $f(x, y)$ be any function locally integrable in $A \supseteq [a, b] \times [c, d]$ (if $b < a$ and/or $d < c$ the definition of A has to be changed accordingly). Also let $(b - a)(d - c)\delta(x, y)$ be the product of the derivatives of $g_1(x)$ and $g_2(y)$. Then:

$$f(g_1(x), g_2(y))\delta(x, y) = \frac{1}{(b - a)(d - c)} \left(\int_c^d dy \int_a^b f(x, y) dx \right) \delta(x, y) \quad (20)$$

where the above product has to be intended as:

$$f(g_1(x), g_2(y))\delta(x, y) = \frac{1}{(b - a)(d - c)} \lim_{n \rightarrow \infty} f(g_{1n}, g_{2n})g'_{1n}g'_{2n} \quad (21)$$

for any pair of sequences g_{1n}, g_{2n} such that:

$$\begin{aligned} 1) & g_{1n}(x), g_{2n}(y) \in C^1 \quad \forall n \in \mathbb{N} \\ 2) & \lim_{n \rightarrow \infty} g_{1n}(x) = g_1(x), \lim_{n \rightarrow \infty} g_{2n}(y) = g_2(y) \\ 3) & \lim_{x \rightarrow -\infty} g_{1n}(x) = a, \lim_{x \rightarrow +\infty} g_{1n}(x) = b \quad \forall n \in \mathbb{N} \\ 4) & \lim_{y \rightarrow -\infty} g_{2n}(y) = c, \lim_{y \rightarrow +\infty} g_{2n}(y) = d \quad \forall n \in \mathbb{N} \\ 5) & g_{1n}(x), g_{2n}(y) \text{ are monotonic } \forall n \in \mathbb{N} \end{aligned} \quad (22)$$

Moreover, we choose each pair $(g_{1n}(x), g_{2n}(y))$ such that, if $(g_{1n}(x), g_{2n}(y))$ are constant in any $]\alpha_1, \beta_1[\times]\alpha_2, \beta_2[$ and equal to (k_1, k_2) , then $f(x, y)$ is continuous in (k_1, k_2) .

Obviously, we can interchange the roles of x and y since we may integrate first with respect of y and then with respect of x . Note that the discontinuity $f(g_1(x), g_2(y))$ addressed by this proposition is not the most general step discontinuity we may have in two dimensions.

As for proposition 1, in order to prove the above proposition, we first need to prove some useful equations. As an example, we will prove the equivalent of the (8). Let $g_{1n}(x), g_{2n}(y)$ be two functions having the characteristics (22) and let $F(x, y)$ be a function such that $F_{xy} = F_{yx} = f(x, y)$. We have:

$$\begin{aligned} & \int_{-\infty}^{+\infty} dy \int_{-\infty}^{+\infty} f(g_{1n}(x), g_{2n}(y))g'_{1n}(x)g'_{2n}(y) dx \\ &= \int_{-\infty}^{+\infty} dy \frac{\partial}{\partial y} \int_{-\infty}^{+\infty} \frac{\partial}{\partial x} F(g_{1n}(x), g_{2n}(y)) dx \\ &= F(b, d) - F(a, d) - F(b, c) + F(a, c) \end{aligned} \quad (23)$$

where, to prove the (23), we have taken the symbol $\frac{\partial}{\partial y}$ inside the integral (for the linearity of integrals) and applied the definition of $F(x, y)$. The (23) is

independent from g_{1n}, g_{2n} and depends only on $f(x, y), a, b, c, d$. Proposition 2 will not be proven in this paper. However, it is possible to prove it by following similar steps to the ones used for proving proposition 1.

Note that proposition 2 gives a clear path on the possible way to generalise the idea of products of step discontinuities and delta functions to the case with as many dimensions as we like.

As a final remark, the fact that proposition 1 and 2 are valid for f locally integrable is an important feature. An example, where we use this feature, is given in paragraph 4 and 5 of this paper.

4 Metrics for a polyhedron vertex

The product of step and delta functions, developed in paragraphs 2 and 3, may be applied to a number of fields of both physics and mathematics where the product of step discontinuity and Dirac delta function arise naturally from the theory. Among all, we have decided to focus our attention to applications related to differential geometry and, in particular, to the evaluation of the curvature for those varieties, described in the introduction, having step discontinuous metric.

As mentioned in the introduction, this kind of variety may have discrete curvature concentrated on edges and vertices. In both cases, Christoffel symbols, Riemann and Ricci tensors, curvature as well as a number of different differential operators, may only be expressed by means of product of step and delta functions. In this case, the relationship between the structures of the step discontinuities and the delta functions codify the geometrical aspects of the non-differentiable point of the surface and proposition 1 (for edges) and proposition 2 (for vertices) turn up to be very useful in finding an expression for the differential quantity of interest

As an example, in this paragraph we will show a convenient and standard way to define a step discontinuous metric for vertices of polyhedra with 3 or 4 concurrent edges, which are very common in many applications, and in paragraph 5 we will show how to use these metrics to evaluate the curvature of that polyhedron in the vertices. Even though this paragraph is focused on curvatures, the same method can be applied to evaluate any kind of differential parameters and operators (e.g. Laplace-Beltrami operators).

Before we proceed, we need to introduce a definition. For the purpose of this paper, we will call a 2d-step function any function defined as follows:

$$s(x_1, x_2) = \begin{cases} r_1 & \text{for } x_1 > 0, x_2 > 0 \\ r_2 & \text{for } x_1 < 0, x_2 > 0 \\ r_3 & \text{for } x_1 < 0, x_2 < 0 \\ r_4 & \text{for } x_1 > 0, x_2 < 0 \end{cases} \quad (24)$$

where $r_i \in \mathbb{R}$ and $s(x_1, x_2)$ is not defined on the axis (x_1, x_2) . Any function of the kind (24) can always be expressed in the form:

$$s(x_1, x_2) = s_0 + s_1(x_1)s_2(x_2) \quad (25)$$

where $s_0 \in \mathbb{R}$ and s_1, s_2 are defined as follows:

$$s_1(x_1) = \begin{cases} a & \text{for } x_1 < 0 \\ b & \text{for } x_1 > 0 \end{cases} \quad (26)$$

$$s_2(x_2) = \begin{cases} c & \text{for } x_2 < 0 \\ d & \text{for } x_2 > 0 \end{cases} \quad (27)$$

and where there is always one degree of freedom in the parameters (s_0, a, b, c, d) . Conversely any function of the form (25) is always a 2d-step function.

Now, let V be a vertex of a polyhedron with 4 edges and angles between edges α, β, γ and θ . Let also S be the surface composed of the vertex, the 4 edges and the relevant 4 faces. We can always open S on a (x_1, x_2) plane by stretching each face by a different amount so that each of the 4 edges lies on one of the semi-axes of the plane. By doing so, we basically map each face of S to a specific sector of the plane (x_1, x_2) . It is easy to see that the metric of S is:

$$g_{ij} = \begin{pmatrix} 1 & s(x_1, x_2) \\ s(x_1, x_2) & 1 \end{pmatrix} \quad (28)$$

where $s(x_1, x_2)$ is a 2d-step function for which the amplitude, in each sector of the (x_1, x_2) plane, is a function of one of the angles $\alpha, \beta, \gamma, \theta$ and the parameters (s_0, a, b, c, d) are defined as follows:

$$s(x_1, x_2) = \begin{cases} \cos(\alpha) = s_0 + bd & \text{for } x_1 > 0, x_2 > 0 \\ -\cos(\beta) = s_0 + ad & \text{for } x_1 < 0, x_2 > 0 \\ \cos(\gamma) = s_0 + ac & \text{for } x_1 < 0, x_2 < 0 \\ -\cos(\theta) = s_0 + bc & \text{for } x_1 > 0, x_2 < 0 \end{cases} \quad (29)$$

The (29) define at the same time $s(x_1, x_2)$ and the equations to determine its parameters. The minus signs in the (29) is to take into account that we are in a sector with one of the two dx_i negative and therefore the angle to consider in the metrics is the one between dx_1 and dx_2 positive which is equal to π minus the angle of the relevant polyhedron face for that sector. Since $\cos(\pi - x) = -\cos(x)$ a minus sign is needed.

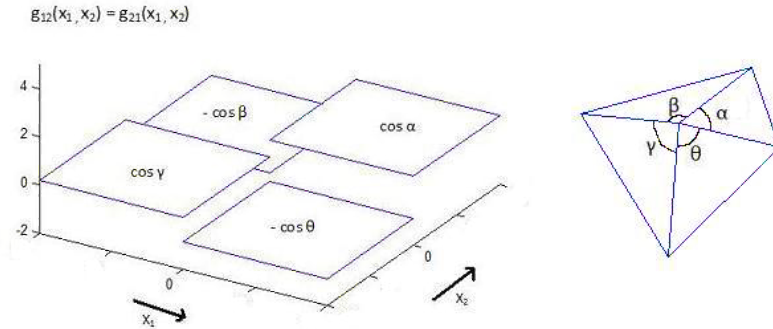


Figure 1: Step discontinuous metric of a polyhedron vertex

As far as vertices with 3 concurrent edges are concerned, we can apply the same procedure by adding a 4th face with angle between edges equal to ϵ and then take the limit for $\epsilon \rightarrow 0$. This is equivalent to cut the surface along one of the edges, open the surface on the plane so that each face corresponds to a sector of the axis (x_1, x_2) while the 4th sector remains uncovered and, finally, assign a null metric to that sector (i.e. $s(x_1, x_2) = 1$). This obviously will lead to an

infinity inverse metric in the sector. This is not a problem since we are mainly interested in evaluating the curvature in the vertex (i.e the discontinuity) and not the curvature on faces and edges (which we know to vanish).

An infinity inverse metric will lead to a function $f(x, y)$, of proposition 2 above, which is continuous in $A =]a, b[\times]c, d[$ and that goes to infinity in one of the point of the border of A (the corner related to the null metric). Since proposition 2 works also for this kind of functions, as long as the function is integrable, this is not really an issue.

5 Vertex curvature and defect angle formula

Given the metric of a vertex defined as for the previous paragraph, we will see now how to evaluate its curvature by means of proposition 2. To do that, we will evaluate all the classical differential parameters, and eventually the curvature, as distributions. First of all we evaluate the $g^{i,j}$. From the (28) we have:

$$g^{ij} = \frac{1}{1-s^2} \begin{pmatrix} 1 & -s \\ -s & 1 \end{pmatrix} \quad (30)$$

The derivatives of the metric are:

$$\Delta_1 = \frac{\partial g_{12}}{\partial x_1} = \frac{\partial g_{21}}{\partial x_1} = (b-a)\delta(x_1)s_2(x_2) \quad (31)$$

$$\Delta_2 = \frac{\partial g_{12}}{\partial x_2} = \frac{\partial g_{21}}{\partial x_2} = (d-c)s_1(x_1)\delta(x_2) \quad (32)$$

all other derivatives vanish. We proceed by evaluating the Christoffel symbol of the first kind. We have:

$$\Gamma_{112} = \frac{1}{2}(-0 + \Delta_1 + \Delta_1) = (b-a)\delta(x_1)s_2(x_2) \quad (33)$$

$$\Gamma_{221} = \frac{1}{2}(-0 + \Delta_2 + \Delta_2) = (d-c)s_1(x_1)\delta(x_2) \quad (34)$$

all other coefficients of the Christoffel symbol of the first kind vanish. For our purpose we need to evaluate only one of the coefficients of the Christoffel symbol of the second kind:

$$\Gamma_{22}^2 = g^{21}\Gamma_{221} + g^{22}\Gamma_{222} = -\frac{(d-c)s}{1-s^2}s_1(x_1)\delta(x_2) \quad (35)$$

We have now all the elements we need to evaluate the Riemann tensor:

$$R_{1212} = \frac{(b-a)(d-c)}{1-s^2}(1-s^2 + s s_1 s_2)\delta(x_1, x_2) \quad (36)$$

for surfaces and given the Riemann tensor, a classical formula for evaluating the curvature is the following:

$$k = \frac{R_{1212}}{g_{11}g_{22} - g_{12}g_{21}} = \frac{R_{1212}}{1-s^2} \quad (37)$$

as expected the curvature is a Dirac delta function in $(0,0)$. This means that the vertex carries a discrete curvature while the curvature on edges and faces

vanishes. The total curvature can be evaluated by integrating the curvature on S :

$$\begin{aligned} k_T &= \iint_S k \sqrt{1-s^2} dx_1 dx_2 = \iint_S R_{1212} \frac{\sqrt{1-s^2}}{1-s^2} dx_1 dx_2 \\ &= (b-a)(d-c) \iint_S (1-s^2 + s s_1 s_2) (1-s^2)^{-\frac{3}{2}} \delta(x_1, x_2) dx_1 dx_2 \end{aligned} \quad (38)$$

since the integrand is impulsive, it is clear that the total curvature is equal to the amplitude of the impulse, which can be evaluated using proposition 2. Before we proceed, we need to justify the fact that proposition 2 works in this case. As long as the metric (28) (i.e. the polyhedron vertex) is the limit of metrics having components s_1 and s_2 , defined by the (25), with characteristics (22) (i.e. the limit of differentiable varieties), then proposition 2 can be used. We have:

$$s_1(x_1) = x; \quad s_2(x_2) = y; \quad s(x_1, x_2) = s_0 + xy; \quad (39)$$

by using the (39) in the (20) we get the final expression for the total curvature:

$$k_T = \int_a^b dy \int_c^d (1-s_0^2 - s_0 xy) [1-s_0^2 - 2s_0 xy - x^2 y^2]^{-\frac{3}{2}} dx \quad (40)$$

integrating, first with respect of x and then with respect of y , we obtain the primitive $F(x, y)$:

$$F(x, y) = \arctan \left(\frac{s_0 + xy}{\sqrt{1 - (s_0 + xy)^2}} \right) \quad (41)$$

Let us see how to use the (41) by checking, for example, the value of $F(x, y)$ in (b, d) . Given the (29) we have:

$$F(b, d) = \arctan \left(\frac{s_0 + bd}{\sqrt{1 - (s_0 + bd)^2}} \right) = \arctan \left(\frac{\cos \alpha}{\sin \alpha} \right) = \frac{\pi}{2} - \alpha \quad (42)$$

where we have used the plus sign of the square root. The minus sign corresponds to the case where we swap all the signs in the (29). This is equivalent to choosing a different mapping, between faces and sectors, of the surface on (x_1, x_2) . From the (40) we evaluate our final results:

$$k_T = F(b, d) - F(a, d) - F(b, c) + F(a, c) = 2\pi - \alpha - \beta - \gamma - \theta \quad (43)$$

which is, as expected, the defect angle formula. It is remarkable that, by means of proposition 2, we have derived the defect angle formula, in a non-differentiable point, by using the tools of differential geometry.

Taking the limit for one of the angles going to zero, we get the example, mentioned at the end of the previous paragraph, of a null metric and an infinite inverse metric in a sector. As anticipated above, in this case the function $f(x, y)$ of proposition 2 goes to infinity (compare with the integrand of (40) above) in a point of the integration set. However, the function is still integrable as clearly shown by the (41) where the primitive is finite in the same point.

Appendix

A.1 Relationship between the (4) and Colombeau theory

We show now the relationship between the (4) and the Colombeau theory. What follows cannot be taken as a formal proof of the (4) for two main reasons:

- The relation (44) below is not true with equality in the Colombeau algebra, but only in the sense of association.
- It is not possible to find a well defined notion of convergence for the series (45) below.

For simplicity, we will use $g(x) = u(x)$, the Heaviside function, and $f \in C^\infty$.

Colombeau coefficients are defined as follows (see [1] §3.3):

$$u^n(x)\delta(x) = \frac{1}{n+1}\delta(x) \quad (44)$$

we have:

$$f(u(x))\delta(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!} u^n(x)\delta(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!(n+1)}\delta(x) \quad (45)$$

where we have used the (44). With the substitution $k = n + 1$ we have:

$$f(u(x))\delta(x) = \sum_{k=1}^{\infty} \frac{f^{(k-1)}(0)}{k!}\delta(x) = \sum_{k=1}^{\infty} \frac{F^{(k)}(0)}{k!}\delta(x) \quad (46)$$

where F is the primitive of f . We have eventually:

$$f(u(x))\delta(x) = \left[-F(0) + \sum_{k=0}^{\infty} \frac{F^{(k)}(0)}{k!} (1)^k \right] \delta(x) = [F(1) - F(0)]\delta(x) \quad (47)$$

A.2 Relaxing the Constrains Given by the (6)

We want to show that the constrains (6) used to prove proposition 1 are too stringent and that, in practical calculations, it is possible to relax them. In particular, in the same hypothesis of proposition 1, we want to remove the 5th constrain of the (6) (i.e. we do not require each element of the sequence $g_n(x)$ to be monotonic). With this new hypothesis, we state that, if

$$\lim_{n \rightarrow \infty} f(g_n(x))g'_n(x) = A\delta(x) \quad (48)$$

which is $f(g_n(x))g'_n(x)$ converges to a delta function, then the amplitude of the delta is given by the (4).

To prove that, we take the limit of the (8) for n that goes to ∞ and, since with sequences of distributions the limit of the integrals is equal to the integral of the limits, we have:

$$\lim_{n \rightarrow \infty} \int_{-\infty}^{+\infty} f(g_n(x))g'_n(x)dx = \int_{-\infty}^{+\infty} A\delta(x)dx = \int_a^b f(x)dx \quad (49)$$

From which we have the (4).

As a final remark, we note that the (48) almost always converges to a delta. As a matter of fact it is very difficult to find a counterexample (I do not have one but, on the other hand, I have not managed to prove that the (48) always converge to a delta either) and therefore condition 5th of the (6) it is not really required in practical calculations. We may say that, as long as the sequence g_n converges to a step discontinuous function (in this case condition 3 and 4 are satisfied as a limit on both x and n), proposition 1 works.

A.3 Discrete Curvature on a Line

We will give below an example where we evaluate the discrete curvature carried by a line. For simplicity we have chosen an example with a continuous metric which is not differentiable on a line. In this case, product of step and delta function are not present in the various differential parameters. However, the same approach can be used for the more general case where the metric is step discontinuous on a line and therefore the use of proposition 1 is required. Let us consider the following surface:

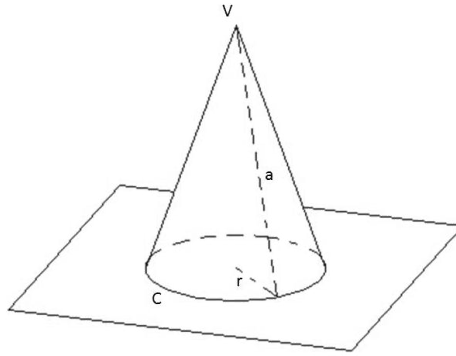


Figure 2: Cone on a Plane

We want to evaluate the discrete curvature carried by C . We evaluate the discrete curvature of the vertex V . To do that, we cut the cone on one side and we unfold it on a plane so that we can use the defect angle formula. We find out easily that the discrete curvature of the vertex V is:

$$k(V) = 2\pi \left(\frac{a-r}{a} \right) \quad (50)$$

We know that the curve C carries a negative discrete curvature, per unit length that compensates exactly the curvature of the vertex:

$$k_T(C) = -k(V) = 2\pi r k(C) \quad (51)$$

where $k_T(C)$ is the total curvature of C and $k(C)$ is the curvature for unit length on C (constant). We have:

$$k(C) = - \left(\frac{a-r}{ar} \right) \quad (52)$$

which completes our calculation.

Now, we want to find the same result by using the methods of differential geometry. We define a polar coordinate system (ρ, θ) on the surface of fig. 2 with the centre on the vertex V , where the coordinate $\rho > 0$ is the distance of the point (ρ, θ) from V evaluated on a minimum distance path (i.e. a ray) and θ is a pseudo-angle covering the whole surface for $\theta \in [0, 2\pi]$. In this coordinate system, the metric of the surface is:

$$ds^2 = \begin{cases} d\rho^2 + \left(\frac{r}{a}\rho\right)^2 d\theta^2 & \text{for } 0 < \rho < a \\ d\rho^2 + (\rho - a + r)^2 d\theta^2 & \text{for } \rho > a \end{cases} \quad (53)$$

which is a continuous but not differentiable function and it is not defined for $\rho = 0$.

We define $\nu(x)$ to be a continuous function such that $\nu'(x) = u(x)$, the Heaviside function, and $\nu(0) = 0$. By using the following notation:

$$\begin{aligned} x_1 &= \rho \\ x_2 &= \theta \\ \alpha_0 &= \frac{r}{a} \\ \alpha_1 &= 1 - \frac{r}{a} \\ m(x_1) &= [\alpha_0 x_1 + \alpha_1 \nu(x_1 - a)]^2 \end{aligned} \quad (54)$$

we have:

$$g_{ij} = \begin{pmatrix} 1 & 0 \\ 0 & m(x_1) \end{pmatrix} \quad (55)$$

$$g^{ij} = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1}{m(x_1)} \end{pmatrix} \quad (56)$$

From now on, we proceed as we did in paragraph 5:

$$\Delta = \frac{\partial g_{22}}{\partial x_1} = 2[\alpha_0 x_1 + \alpha_1 \nu(x_1 - a)][\alpha_0 + \alpha_1 u(x_1 - a)] \quad (57)$$

$$\Gamma_{221} = -\frac{1}{2}\Delta \quad (58)$$

$$\Gamma_{212} = \Gamma_{122} = \frac{1}{2}\Delta \quad (59)$$

all other coefficients of the Christoffel symbol of the first kind vanish.

$$\Gamma_{21}^2 = g^{21}\Gamma_{211} + g^{22}\Gamma_{212} = \frac{\Delta}{2m} \quad (60)$$

and finally, if we do not write the terms that vanish, we have:

$$R_{1212} = \frac{\partial \Gamma_{221}}{\partial x_1} + \Gamma_{122}\Gamma_{21}^2 \quad (61)$$

$$= -\frac{1}{2} \frac{\partial \Delta}{\partial x_1} + \frac{\Delta^2}{4m} \quad (62)$$

$$= -\alpha_0 \alpha_1 x_1 \delta(x_1 - a) - (\alpha_1)^2 \nu(x_1 - a) \delta(x_1 - a) \quad (63)$$

The curvature of the surface is:

$$k = \frac{R_{1212}}{g_{11}g_{22} - g_{12}g_{21}} = \frac{R_{1212}}{m} \quad (64)$$

Let ϵ be any number such that $0 < \epsilon < a$, the total curvature of the surface can be evaluated as:

$$k_T = \iint_S k \sqrt{m} dx_1 dx_2 \quad (65)$$

$$= \int_{\epsilon}^{\infty} \int_0^{2\pi} R_{1212} m^{-\frac{1}{2}} dx_1 dx_2 \quad (66)$$

$$= -2\pi \alpha_1 \int_{\epsilon}^{\infty} \delta(x_1 - a) dx_1 \quad (67)$$

$$= -2\pi \left(\frac{a - r}{a} \right) = k_T(C) \quad (68)$$

as expected. This example is quite trivial. However, the same method can be extended to generic curves where a direct geometrical approach, as the one used at the beginning of this paragraph, cannot be used.

A.4 Structure of a Discontinuity

We want to give a new interpretation of the theory developed in paragraph 2 and 3 above. Since any discontinuous point of a distribution can be defined by the limit of a sequence of function, we define the structure of a discontinuity to be the specific sequence of functions used to define it. Products of distributions strongly depend from the structure of the various discontinuities which are multiplied and in the particular case of the (4) and (20), the structure of the discontinuity is fully represented by the function f .

Equations (4) and (20) focus their attention only on the structure of step discontinuities and the way they are modified (by composition with a locally integrable function f). When it comes to Dirac delta functions, it is possible to show that they change their own structure by means of multiplication by step discontinuous functions.

Let us consider the function $f(g(x))$ where g is a step discontinuous function, jumping from a to b in 0 , and $f \in L_{loc}^1([a, b])$. Since we may define our function as the limit of a sequence of functions $f(g_n(x))$ with $g_n(x) \in C^1$, and since the Leibniz rule may be applied to each term of the sequence, we will suppose that we can apply the Leibniz rule also to its limit. This point should be further justified but we give it for true in this informal discussion. We have:

$$Df(g(x)) = (b - a)f'(g(x))\delta(x) \quad (69)$$

from which we see that the structure of the delta function $f'(g(x))\delta(x)$ is related (and charges with it) to the structure of the step discontinuous function $f(g(x))$ just by being its derivative. So, given the structure of $u(x)$, a suitable function f can be used to describe the structure of any step or delta function.

We have seen that with products of distributions, if we change the structure of a term we get a different result. In order to overcome this limitation, we want now to extend the space of distributions D' by adding to it, as separate

generalised functions, additional elements representing any possible discontinuity structure needed for describing products of step and delta functions. Let us call this space $G^u \supset D'$.

We will use the following notation:

$$\begin{aligned} u_{[f(x)]} &= f(u(x)) \in G^u && \text{step function having structure } f \\ \delta_{[f'(x)]} &= f'(u(x))\delta(x) \in G^u && \text{delta function having structure } f \end{aligned} \quad (70)$$

where $u_{[f(x)]}$ and $\delta_{[f'(x)]}$ are not normalised (i.e they may have amplitude different from 1). We have:

$$\begin{aligned} u_{[x]} &= u(x) \in D' \\ \delta_{[1]} &= \delta(x) \in D' \end{aligned} \quad (71)$$

We will show, with an example at the end of this paragraph, that the above defined generalised functions have components outside D' and therefore there is a need for defining a larger space of generalised functions including D' .

Using the (70), we define the multiplication as follows:

$$u_{[f_1]}u_{[f_2]} \cdot \dots \cdot u_{[f_n]}\delta_{[f_{n+1}]} = \delta_{[f_1 f_2 \dots f_n f_{n+1}]} \quad (72)$$

This product is commutative and associative since commutative and associative is the product of the f_i functions used in the definition of the (72).

Finally we define a projector operator $P_{D'}$, which projects any generalised function in G^u , on the space D' . For step discontinuous functions the way $P_{D'}$ works is trivial (e.g. $u^2(x)$ goes to $u(x)$). For delta functions, we apply the (4), we have:

$$P_{D'}(\delta_{[f_1 f_2 \dots f_n f_{n+1}]}) = \left(\int_0^1 f_1 f_2 \cdot \dots \cdot f_n f_{n+1} dx \right) \delta(x) \in D' \quad (73)$$

where the integration is performed between 0 and 1, which is the jump of our reference step discontinuity $u(x)$.

Let us make an example. Consider the product of distributions $sign^2(x)\delta(x)$ (compare with [2] §1.1 ex. iii). By using proposition 1 we find easily that:

$$sign^2(x)\delta(x) = \frac{1}{3}\delta(x) \quad (74)$$

Let us check associativity by using, once again, proposition 1:

$$sign^2(x)\delta(x) = sign(x)[sign(x)\delta(x)] = sign(x) \cdot 0 = 0 \quad (75)$$

we conclude that, in D' , our product is not associative. Let us see what happen in G^u :

$$sign(x)[sign(x)\delta(x)] = sign(x)\delta_{[(2x-1) \cdot 1]} = sign(x)[\delta_{[2x]} - \delta_{[1]}] \quad (76)$$

In D' , $\delta_{[1]} = \delta$ and $P_{D'}(\delta_{[2x]}) = \delta$. However, in G^u they are separate objects and they do not cancel each other. We have eventually:

$$sign^2(x)\delta(x) = P_{D'}(\delta_{[(2x-1)^2]}) = \frac{1}{3}\delta(x) \quad (77)$$

A.5 Examples of Products of Steps and Delta Functions

Example 1:

$$\int_{-\infty}^{+\infty} \frac{d}{dx} u^2(x) dx = [u^2(x)]_{-\infty}^{+\infty} = 1 = 2 \int_{-\infty}^{+\infty} u(x) \delta(x) dx \quad (78)$$

from which we have:

$$u(x) \delta(x) = \frac{1}{2} \delta(x) \quad (79)$$

in agreement with proposition 1.

Example 2:

Given

$$\delta(x) = \frac{1}{2} \frac{d}{dx} \text{sign}(x) \quad (80)$$

and

$$1(x) = -1 + \frac{1}{1 - \frac{1}{2} \text{sign}^2(x)} \quad (81)$$

by using proposition 1 we have:

$$1(x) \delta(x) = \frac{1}{2} \left[\int_{-1}^{+1} \frac{x^2}{2-x^2} dx \right] \delta(x) = \left[\frac{\sqrt{2}}{2} \ln \left(\frac{2+\sqrt{2}}{2-\sqrt{2}} \right) - 1 \right] \delta(x) \quad (82)$$

Note that $1(x)$ in D' is the constant function 1 and therefore it has not even a step discontinuity.

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