Does the Continuity Equation Imply Maxwell's Equations?

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The antiderivative of a divergence free multivector field is shown to be curl free up to a harmonic function. This result implies that *any* vector valued current density J that is divergence free possesses a bivector valued antiderivative F that satisfies $\partial F = J$ under suitable boundary conditions. In four dimensions, this is Maxwell's equation. This reinforces an existing result indicating that charge conservation can serve as a foundation for an axiomatic formulation of electrodynamics.

Work In Progress This paper is a work in progress and is being openly developed on Github at `https://github.com/lukeburns/maxwells-equations`. Contributions are warmly welcomed, whether by means of opening an issue or pull request.

1 Introduction

The question *Can Maxwells equations be obtained from the continuity equation?* was first asked by José A. Heras in [1], who concluded *yes* and provided a construction by means of a generalization of Helmholtz decomposition. The purpose of the present paper is to affirm and generalize the theorem of Heras to manifolds of any dimension by means of a generalized Helmholtz decomposition of geometric calculus.

After establishing a mapping between n-vector fields and differential forms of degree n, which allows for the result of this paper to be translated into differential forms, I present the Fundamental Theorem of Geometric Calculus, and two consequences: a generalization of Cauchy's Integral Formula and Helmholtz decomposition for multivector fields.

Using these results, I show that all divergence free (coclosed) fields fail to be coexact (i.e. the curl of some other field) by at most a monogenic term. Monogenic fields are characterized by the property that they are fully determined by boundary conditions, analogous to complex analytic functions. I present some conditions under which these fields are coexact. A field whose antiderivative is curl free is dubbed *faithful*, by which it follows that the derivative of a curl free field is faithful, and the antiderivative of a faithful field is curl free. This establishes an equivalence between the statements "an electromagnetic field F is a curl free bivector field" and "an electromagnetic current J is a faithful vector field," both of which fully determine the structure of Maxwell's equations.

I then show that a conserved vector field J is faithful on a simple manifold of arbitrary dimension under suitable boundary conditions. This reinforces the result of Heras that the continuity equation implies Maxwell's equations, under satisfactory boundary conditions.

2 Fields and forms

If $F_n \equiv \langle F \rangle_n$ is the grade n part of the multivector field (hereafter, just field) $F = \sum F_n$ in an arbitrary geometric algebra $\mathcal{G}$, then its corresponding *differential form* f_n of *degree* n is a scalar field given by [2]

$$f_n \equiv d^n x^\dagger \cdot F_n, \tag{1}$$

which is the projection of the n-vector field F_n onto the directed measure $d^n x^\dagger = dx_n \wedge \cdots \wedge dx_1$, where dx_i are vector valued differentials.

The hodge star operation $*$ acts on fields as

$$* F \equiv F^\dagger I, \tag{2}$$

where I is the pseudoscalar of some oriented vector manifold.[^1]

The exterior derivative d behaves identically to the curl

$$df_n \equiv d^{n+1} x^\dagger \cdot (\partial \wedge F_n), \tag{3}$$

and the "adjoint operator" δ behaves identically to (minus) the divergence

$$\delta f_n \equiv d^{n-1} x^\dagger \cdot (-\partial \cdot F_n). \tag{4}$$

The word *form* will be reserved for scalar fields corresponding to some n-vector field via Equation 1. Lowercase letters will be used for forms and uppercase letters for fields. Subscripts denote grade of a multivector (degree of a form).

3 Derivatives

A field F is called *curl free* (or closed) when

$$\partial \wedge F = 0 \tag{5}$$

and *divergence free* (or coclosed) when

[^1]: See Chapter 4 of [2], or Section 6.5 of [4].

$$\partial \cdot F = 0, \tag{6}$$

where $\partial = \partial_x$ is the derivative with respect to the vector x. This operator is unique to geometric calculus, and the entire subject is a study of the properties of this operator. It's also often called the Dirac operator and can be written $\partial = e^k \partial_k$ where $\partial_k = \frac{\partial}{\partial x^k} = e_k \cdot \partial$ with respect to coordinates $x^k = e_k \cdot x$.[2]

A field for which

$$\partial F = \partial \cdot F + \partial \wedge F = 0 \tag{7}$$

is called *monogenic*. It possesses the property of complex analytic functions that, in any region, it is fully determined by its values on the boundary of that region. Hence, the form ω is closed if $d\omega = 0$, coclosed if $\delta\omega = 0$, and monogenic if $d\omega = \delta\omega = 0$. Note that for general fields, $\partial F = 0$ does not necessarily imply that $\nabla \cdot F = \nabla \wedge F = 0$.

A field H that satisfies

$$\partial^2 H = 0 \tag{8}$$

might be called *harmonic*, although the term is inappropriate in mixed signature spaces. For instance, in Minkowski space, $\partial^2 H = (\partial_t^2 - \vec{\nabla}^2)H = 0$ is the wave equation and its properties differ dramatically from the usual harmonic functions in Euclidean spaces. Nonetheless, I will abuse the term here for lack of a better one. A form γ is then harmonic if $d\delta\gamma + \delta d\gamma = 0$.

4 Potentials

If a field J is written as

$$J = \partial \cdot G + \partial \wedge H, \tag{9}$$

then G and H are called *potentials* for J. Similarly, if a form ω is given by

$$\omega = d\alpha + \delta\beta \tag{10}$$

then α and β will be called potentials for ω.

A field J is called *exact* when

$$J = \partial \wedge F \tag{11}$$

and *coexact* when

$$J = \partial \cdot F, \tag{12}$$

whereby a form ω is exact if $\omega = d\alpha$ and coexact if $\omega = \delta\beta$. Two curl free fields are called *cohomologous* if their difference is an exact field. Similarly, two divergence free fields are called *homologous* if their difference is a coexact field.

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[2]See p. 252 of [2] for a coordinate free, integral definition of ∂.

5 Antiderivatives

A field F is called an *antiderivative* of J if

$$J = \partial F = \partial \cdot F + \partial \wedge F, \tag{13}$$

which is unique up to a monogenic term. That is, $F + C$ such that $\partial C = 0$ is also an antiderivative. Furthermore, given an antiderivative, one has possession of constraints on F. For every $J_k = 0$ (again, where $J_k = \langle J \rangle_k$ is the k-grade part of J),

$$J_k = \partial \cdot F_{k+1} + \partial \wedge F_{k-1} = 0. \tag{14}$$

As an example, if $J = J_n$ is an n-vector field, then

$$J_n = \partial F = \partial \cdot F_{n+1} + \partial \wedge F_{n-1}, \tag{15}$$

and the constraints due to $J_{n-2} = J_{n+2} = 0$ and $F_{n-3} = F_{n+3} = 0$ are

$$J_{n-2} = \partial \cdot F_{n-1} = 0 \text{ and } J_{n+2} = \partial \wedge F_{n+1} = 0. \tag{16}$$

Of course, F *could* contain terms of higher and lower grades as long as they vanish under the derivative, but they make no contribution to J_n. Under the restriction that it only has grades which contribute to J_n, F is of the form

$$F = F_{n-1} + F_{n+1}. \tag{17}$$

If j_n and f_n are the forms given by J_n and F_n, then Equations 3 and 4 imply that, in terms of differential forms, Equation 15 is of the form

$$j_n = -\delta f_{n+1} + df_{n-1}, \tag{18}$$

and Equation 16 is equivalent to

$$\delta f_{n-1} = df_{n+1} = 0. \tag{19}$$

Given potentials f_{n-1} and f_{n+1} under these constraints, one is in possession of an antiderivative of j_n.

6 The Fundamental Theorem

Let $\mathcal{M}$ be an m-dimensional smooth oriented vector manifold with a piecewise smooth boundary $\partial\mathcal{M}$ and L be a linear function, differentiable on $\mathcal{M}$ and $\partial\mathcal{M}$. Then, [2] [3] [4]

$$\int L(\dot{x}, d^m x \dot{\partial}) = \oint L(x, d^{m-1}x), \tag{20}$$

where $L(\dot{x}, d^m x \dot{\partial})$ denotes right and left differentiation all x dependent terms in L by ∂. Note that the linear function L is multivector-valued and Stokes' theorem of differential forms is equivalent to the scalar valued part

$$\int \langle L(\dot{x}, d^m x \dot{\partial}) \rangle = \oint \langle L(x, d^{m-1}x) \rangle. \tag{21}$$

7 Integral Formula

Let J be a field on a simple (not self-intersecting) manifold $\mathcal{M}$ subject to the same criteria in the fundamental theorem. Suppose J satisfies the equation

$$\partial F = J. \tag{22}$$

Then F is given by [2]

$$
\begin{aligned}
F(x) = &+ (-1)^m I^{-1}(x) \int g(x,x') d^m x' J(x') \\
&- (-1)^m I^{-1}(x) \oint g(x,x') d^{m-1} x' F(x'),
\end{aligned}
\tag{23}
$$

where g is a Green's function of ∂ satisfying $\partial g(x,x') = -g(x,x')\partial' = \delta(x-x')$. This result says that *any integrable field has a local antiderivative, and it's given by Equation 23.*

Helmholtz decomposition Notice that the integral formula is simply a generalized Helmholtz decomposition, since

$$J = \partial F = \partial \cdot F + \partial \wedge F, \tag{24}$$

is a decomposition of J into divergence free and curl free fields, $\partial \cdot F$ and $\partial \wedge F$ respectively. This is because $\partial \wedge (\partial \wedge M) = \partial \cdot (\partial \cdot M) = 0$ for any field M. Additionally, this decomposition comes with constraints given by Equation 14.

The corresponding result for forms is that locally, for any n-form j_n, there exists an $n+1$-form f_{n+1} and an $n-1$-form f_{n-1}, such that

$$j_n = -\delta f_{n+1} + d f_{n-1}, \tag{25}$$

with the constraints $df_{n+1} = \delta f_{n-1} = 0$. Note that this is a stronger result than Helmholtz decomposition due to the constraints on f_{n-1} and f_{n+1} and stronger than Hodge decomposition due the fact that it is *not* restricted to Riemannian manifolds.

8 Divergence and curl free fields

The above result implies that antiderivatives of divergence free fields fail to be curl free, and antiderivatives of curl free fields fail to be divergence free, by at most a harmonic function H satisfying $\partial^2 H = 0$.

Suppose J is divergence free (the dual result for curl free fields follows analogously). By the integral formula, it has a local antiderivative F, such that $J = \partial F$. Hence,

$$\partial \cdot J = \partial \cdot (\partial F) = \partial \cdot (\partial \cdot F + \partial \wedge F) = \partial \cdot (\partial \wedge F) = \partial(\partial \wedge F) = 0, \tag{26}$$

which means that $C \equiv \partial \wedge F$ is monogenic and J is locally homologous with C

$$J - C = \partial F - C = \partial \cdot F, \tag{27}$$

because their difference is coexact.

Employing the integral theorem, C has an antiderivative H such that

$$C = \partial H. \tag{28}$$

With $G \equiv F - H$, this implies that F can then be written

$$F = G + H \tag{29}$$

where $\partial G = \partial \cdot F$ and $\partial^2 H = 0$. Note that if $H = 0$, then $\partial F = \partial \cdot F$. Hence, F fails to be curl free by at most a harmonic function H.

As an example, if C is a monogenic r-vector field, then C can be written $C = \partial \cdot (x \wedge C)/r = \partial \wedge (x \cdot C)/(n-r)$, and C is both exact and coexact, in which case[3]

$$J = \partial F = \partial \cdot (F + x \wedge C/r) \tag{30}$$

is locally coexact — although, F is not curl free.

If $C = 0$ on the boundary, then $C = 0$ everywhere, and its antiderivative is curl free

$$J = \partial F = \partial \cdot F. \tag{31}$$

Let us call a field J *faithful* if its antiderivative is curl free. Faithful fields are coexact, and all divergence free fields differ from faithful fields by at most a monogenic field, which depends solely on the manifold and boundary conditions. Note, however, that coexact fields are not necessarily faithful.

A form is faithful if

$$j = -\delta f \text{ and } df = 0. \tag{32}$$

A field J with a divergence free antiderivative F is *cofaithful* and can be written

$$J = \partial F = \partial \wedge F, \tag{33}$$

and hence, a form is cofaithful if

$$j = df \text{ and } \delta f = 0. \tag{34}$$

9 Conserved currents

Consider the specific case of a divergence free vector field J (i.e. a conserved current). By Equation 16 and Equation 29, any antiderivative F of J can be decomposed into

$$F = F_0 + F_2, \tag{35}$$

such that

$$\partial F = \partial \cdot F_2 + \partial F_0 = J, \tag{36}$$

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[3]Under what conditions are general monogenic multivector fields exact / coexact?

where $\partial \wedge F_2 = 0$ and $\partial^2 F_0 = 0$. *Any* divergence free vector field J can be written in this form, in regions where J is integrable.

This is an important result, particularly in flat spacetime, so I'll write it out in the familiar vector algebra of three dimensions by splitting $\partial = \gamma^0(\frac{1}{c}\partial_t + \vec{\nabla})$, $F_2 = \vec{E} + i\vec{B}$, and $J = (c\rho + \vec{J})\gamma_0$ into frame dependent timelike and spacelike terms. In four dimensions, with $\chi \equiv F_0$, Equation 36 can be decomposed into

$$\vec{\nabla} \cdot \vec{E} + \frac{1}{c}\partial_t\chi = c\rho \qquad\qquad \vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \times \vec{B} - \vec{\nabla}\chi = \frac{1}{c}\partial_t E + \vec{J} \qquad \vec{\nabla} \times \vec{E} = -\frac{1}{c}\partial_t B. \tag{37}$$

That is, Equation 37 is equivalent to the continuity equation in flat spacetime.

On suitable manifolds and under suitable boundary conditions, J is locally faithful. Equation 24 tells us that J can be written

$$J = (-1)^m I^{-1} \left(\int g d^m x \partial J - \oint g d^{m-1} x J \right). \tag{38}$$

For instance, if the boundary term vanishes, then J is given by

$$J = (-1)^m I^{-1} \int g d^m x \partial J, \tag{39}$$

which is only dependent on $\partial J = \partial^2 F = \partial^2(F_0 + F_2) = \partial^2 F_2$, since F_0 is harmonic. In other words, when J is fully determined by its derivative ∂J, J is independent of F_0 and J can generally be written as

$$J = \partial F = \partial \cdot F, \tag{40}$$

and J is faithful. Equation 37 is then equivalent to Maxwell's equations

$$\vec{\nabla} \cdot \vec{E} = c\rho \qquad\qquad \vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \times \vec{B} = \frac{1}{c}\partial_t E + \vec{J} \qquad \vec{\nabla} \times \vec{E} = -\frac{1}{c}\partial_t B. \tag{41}$$

This affirms the result of Heras that Maxwell's equations can be obtained from the continuity equation.[1]

Maxwell's equations follow from directly from the statement that *"an electromagnetic field F is a curl free bivector field and its derivative is its current J."* To say that it is curl free means that

$$\partial \wedge F = 0, \tag{42}$$

and its derivative J is

$$J = \partial F = \partial \cdot F, \tag{43}$$

which are Maxwell's equations with no magnetic monopoles or currents. Of course, Maxwell's equations imply the continuity equation

$$\partial \cdot J = \partial \cdot (\partial \cdot F) = 0, \tag{44}$$

which means charge is conserved.

The result of this paper allows for an alternative characterization of Maxwell's equations. F is an antiderivative of J, so to say that F is curl free is the same as saying J is faithful. Hence, the above characterization is equivalent to the dual statement *"an electromagnetic current J is a faithful vector field and its antiderivative is an electromagnetic field F."*

References

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