An extrinsic look at the Riemannian Hessian

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Abstract. Let f be a real-valued function on a Riemannian submanifold of a Euclidean space, and let $\bar{f}$ be a local extension of f. We show that the Riemannian Hessian of f can be conveniently obtained from the Euclidean gradient and Hessian of $\bar{f}$ by means of two manifold-specific objects: the orthogonal projector onto the tangent space and the Weingarten map. Expressions for the Weingarten map are provided on various specific submanifolds.

Keywords: Riemannian Hessian, Euclidean Hessian, Weingarten map, shape operator

1 Introduction

This paper concerns optimization methods on Riemannian manifolds that make explicit use of second-order information. This research area is motivated by various problems in the sciences and engineering that can be formulated as optimizing a real-valued function defined on a Riemannian manifold (see, e.g., [20,16,17,12,7] for some recently considered applications), and by the well-known fact that second-order methods tend to have the edge over first-order methods in situations where an accurate solution is sought or when the Hessian gets ill conditioned (see [1] for a recent example).

The archetypical second-order optimization method is Newton's method, of which several generalizations have been proposed on manifolds. Most of them fit in the framework given in [19,5] and [2, Alg. 5]. Besides a smooth real-valued function f defined on a Riemannian manifold $\mathcal{M}$, the ingredients of the Riemannian Newton method [2, Alg. 5] are an affine connection ∇ on $\mathcal{M}$ and a retraction R on $\mathcal{M}$. Turning the Riemannian Newton method into a successful numerical algorithm relies much on choosing ∇ and R and on computing them efficiently.

A retraction R on $\mathcal{M}$ can be viewed as a tool that turns a tangent update vector into a new iterate on $\mathcal{M}$. Retractions have been given particular attention in the recent literature, in general [3] and also specifically for the important cases where $\mathcal{M}$ is the Stiefel manifold of orthonormal matrices [15,21,13] or the manifold of fixed-rank matrices [20,18].

As for the affine connection ∇, it is instrumental in the definition of the Hessian operator of f on $\mathcal{M}$. Namely, for all $x \in \mathcal{M}$ and all z in the tangent space $\mathrm{T}_x\mathcal{M}$, one defines

$$\operatorname{Hess} f(x)[z] := \nabla_z \operatorname{grad} f \quad \in \mathrm{T}_x\mathcal{M}. \tag{1}$$

While the convergence analysis of the Riemannian Newton method in [2, §6.3] provides for using any affine connection, a natural choice for ∇ is the uniquely defined Riemannian connection, also termed Levi-Civita connection or canonical connection.

In this paper, for the case where $\mathcal{M}$ is a Riemannian submanifold of a Euclidean space $\mathcal{E}$ (examples can be found in Section 4) and where ∇ is chosen to be the Riemannian connection, we give a formula for the Hessian (1) that relies solely on four objects: (i) the classical gradient $\partial \bar{f}(x)$ of a smooth extension $\bar{f}$ of f in a neighborhood of $\mathcal{M}$ in $\mathcal{E}$, (ii) the classical Hessian $\partial^2 \bar{f}(x)$ of $\bar{f}$, (iii) the orthogonal projector $\mathcal{P}_x$ onto $\mathrm{T}_x\mathcal{M}$, (iv) the *Weingarten map* $\mathfrak{A}_x$, also called *shape operator*. (The symbol $\mathfrak{A}$ is "A" in Fraktur font.) We provide expressions for $\mathcal{P}_x$ and $\mathfrak{A}_x$ on some important Riemannian submanifolds. These expressions yield a formula for the Riemannian Hessian where f is involved only through the classical gradient and Hessian, $\partial \bar{f}(x)$ and $\partial^2 \bar{f}(x)$. These results can be exploited in various Riemannian optimization schemes, such as Newton's method or trust-region methods, where the knowledge of the Hessian is either mandatory or potentially beneficial.

The paper is organized as follows. Section 2 recalls in more details the definition of the Riemannian Hessian on submanifolds of Euclidean spaces. Section 3 lays out the relation between the Riemannian Hessian and the Weingarten map. Finally, section 4 provides formulas for the Weingarten map on several specific manifolds.

An early version of Sections 2 and 3 of this paper can be found in section 6 of the technical report [4].

2 The Riemannian Hessian on submanifolds

Let $\mathcal{M}$ be a d-dimensional Riemannian submanifold of an n-dimensional Euclidean space $\mathcal{E}$; see, e.g., [2, §3.6.1] or [9, §2.A.3] for details. Let x_0 be a point of $\mathcal{M}$, let f be a smooth real-valued function on $\mathcal{M}$ around x_0, and let $\bar{f}$ be a smooth extension of f to a neighborhood $\mathcal{U}$ of x_0 in $\mathcal{E}$.

For all $x \in \mathcal{M}$, we let $\partial \bar{f}(x)$ and $\partial^2 \bar{f}(x)$ denote the (Euclidean) gradient and (Euclidean) Hessian of $\bar{f}$ at x. In coordinates, we have

$$\partial \bar{f}(x) = \left[\partial_1 \bar{f}(x) \ \ldots \ \partial_n \bar{f}(x)\right]^{\mathrm{T}}$$

and

$$[\partial^2 \bar{f}(x)]_{ij} = \partial_{ij} \bar{f}(x), \quad i, j = 1, \ldots, n.$$

We also let $\mathcal{P}_x$ denote the orthogonal projector onto $\mathrm{T}_x\mathcal{M}$, defined by

$$\mathcal{P}_x : \mathrm{T}_x\mathcal{E} \simeq \mathcal{E} \ \rightarrow \ \mathrm{T}_x\mathcal{M} \ : \ \xi \mapsto \mathcal{P}_x(\xi) \tag{2}$$

with $\langle \xi - \mathcal{P}_x(\xi), \zeta \rangle = 0$ for all $\zeta \in \mathrm{T}_x\mathcal{M}$. Examples will be given in Section 4. Once an orthonormal basis is chosen for $\mathcal{E}$, $\mathcal{P}_x$ is represented as a (symmetric) matrix; hence $\mathcal{P}$ can be viewed as a matrix-valued function on $\mathcal{M}$. For any function F on $\mathcal{M}$ into a vector space, and for any $z \in \mathrm{T}_x\mathcal{M}$, we let

$$\mathrm{D}_z F = \lim_{t \to 0} F(\gamma(t)),$$

where γ is any curve on $\mathcal{M}$ with $\gamma(0) = x$ and $\gamma'(0) = z$.

We have

$$\operatorname{grad} f(x) = \mathcal{P}_x \partial \bar{f}(x), \tag{3}$$

where $\operatorname{grad} f(x)$ denotes the (Riemannian) gradient of f at x; see [2, §3.6.1] for details. Moreover, letting ∇ denote the Riemannian connection on $\mathcal{M}$, we have that $\operatorname{Hess} f(x)$, the Riemannian Hessian of f at x, is the linear transformation of $\mathrm{T}_x\mathcal{M}$ defined, for all $z \in \mathrm{T}_x\mathcal{M}$, by

$$\begin{aligned}
\operatorname{Hess} f(x)[z] &= \nabla_z \operatorname{grad} f &(4)\\
&= \mathcal{P}_x \mathrm{D}_z \left(\operatorname{grad} f\right) &(5)\\
&= \mathcal{P}_x \mathrm{D}_z \left(\mathcal{P} \partial \bar{f}\right) &(6)\\
&= \mathcal{P}_x \partial^2 \bar{f}(x) z + \mathcal{P}_x \mathrm{D}_z \mathcal{P} \partial \bar{f}(x). &(7)
\end{aligned}$$

Equation (4) is the definition (1). Equation (5) comes from the classical expression of the Riemannian connection on a Riemannian submanifold of a Euclidean space; see, e.g., [2, §5.3.3] or [9, §2.B.2]. Equation (6) follows from (3). Finally, (7) is an application of the product rule, observing that $\mathcal{P}$ is a matrix-valued function, $\partial \bar{f}$ a vector-valued function, and $\mathcal{P}_x \mathcal{P}_x = \mathcal{P}_x$ since $\mathcal{P}_x$ is a projector.

Expression (7) features the four ingredients alluded to in the introduction, namely $\partial \bar{f}(x)$, $\partial^2 \bar{f}(x)$, $\mathcal{P}_x$, $\mathcal{P}_x \mathrm{D}_z \mathcal{P}$. The rest of this paper is devoted to establishing the relation of $\mathcal{P}_x \mathrm{D}_z \mathcal{P}$ with the Weingarten map and to working out formulas for $\mathcal{P}_x \mathrm{D}_z \mathcal{P}$ on various specific Riemannian submanifolds.

3 The Riemannian Hessian and the Weingarten map

We are thus concerned with $\mathcal{P}_x \mathrm{D}_z \mathcal{P}$, where $z \in \mathrm{T}_x\mathcal{M}$. In this section, we establish a relation (8) between $\mathcal{P}_x \mathrm{D}_z \mathcal{P}$ and the Weingarten map, defined next. This relation does not seem to have been previously pointed out in the literature, but it is present in the technical report [4].

Definition 1 (Weingarten map). *The* Weingarten map *of the submanifold $\mathcal{M}$ at x is the operator $\mathfrak{A}_x$ that takes as arguments a tangent vector $z \in \mathrm{T}_x\mathcal{M}$ and a normal vector $v \in \mathrm{T}_x^\perp\mathcal{M}$ and returns the tangent vector*

$$\mathfrak{A}_x(z, v) = -\mathcal{P}_x \mathrm{D}_z V,$$

where V is any local extension of v to a normal vector field on $\mathcal{M}$.

It is known [6, Prop. II.2.1] that $\mathcal{P}_x \mathrm{D}_z V$ does not depend on the choice of the extension V, and this makes the above definition valid. The next result confirms this fact and gives an alternate expression of $\mathfrak{A}_x(z, v)$. Let

$$\mathcal{P}_x^\perp = I - \mathcal{P}_x$$

denote the orthogonal projector onto the normal space to $\mathcal{M}$ at x. It is useful to keep in mind that, in our convention, D applies only to the expression that directly follows: $\mathrm{D}_z FG = (\mathrm{D}_z F)G \neq \mathrm{D}_z(FG)$.

Theorem 1. *The Weingarten map $\mathfrak{A}_x$ satisfies*

$$\mathfrak{A}_x(z, \mathcal{P}_x^\perp u) = \mathcal{P}_x \mathrm{D}_z \mathcal{P} u = \mathcal{P}_x \mathrm{D}_z \mathcal{P}\mathcal{P}_x^\perp u, \tag{8}$$

for all $x \in \mathcal{M}$, $z \in \mathrm{T}_x\mathcal{M}$, and $u \in \mathrm{T}_x\mathcal{E} \simeq \mathcal{E}$.

Proof. We first show that

$$\mathcal{P}_x \mathrm{D}_z \mathcal{P} = \mathcal{P}_x \mathrm{D}_z \mathcal{P}\mathcal{P}_x^\perp, \tag{9}$$

which takes care of the second equality in (8). Since $\mathcal{P}\mathcal{P}^\perp = 0$, we have $0 = \mathrm{D}_z \mathcal{P}\mathcal{P}_x^\perp + \mathcal{P}_x \mathrm{D}_z \mathcal{P}^\perp = \mathrm{D}_z \mathcal{P}\mathcal{P}_x^\perp - \mathcal{P}_x \mathrm{D}_z \mathcal{P}$. It follows that $\mathcal{P}_x \, \mathrm{D}_z \mathcal{P} \, \mathcal{P}_x = 0$. Hence, since $\mathcal{P}_x + \mathcal{P}_x^\perp = I$, we have $\mathcal{P}_x \mathrm{D}_z \mathcal{P} = \mathcal{P}_x \mathrm{D}_z \mathcal{P}(\mathcal{P}_x + \mathcal{P}_x^\perp) = \mathcal{P}_x \, \mathrm{D}_z \mathcal{P} \, \mathcal{P}_x + \mathcal{P}_x \, \mathrm{D}_z \mathcal{P} \, \mathcal{P}_x^\perp = \mathcal{P}_x \, \mathrm{D}_z \mathcal{P} \, \mathcal{P}_x^\perp$, and the claim (9) is proven.

For the first equality in (9), we have, for all extension U of u,

$$-\mathcal{P}_x \mathrm{D}_z(\mathcal{P}^\perp U) = -\mathcal{P}_x \mathrm{D}_z \mathcal{P}^\perp U - \mathcal{P}_x \mathcal{P}_x^\perp \mathrm{D}_z U = -\mathcal{P}_x \mathrm{D}_z \mathcal{P}^\perp U = \mathcal{P}_x \mathrm{D}_z \mathcal{P} U.$$

This concludes the proof.

A consequence of Theorem 1 for the Riemannian Hessian expression (7) is that $\mathcal{P}_x \mathrm{D}_z \mathcal{P} \partial \bar{f}(x) = \mathcal{P}_x \mathrm{D}_z \mathcal{P}\mathcal{P}_x^\perp \partial \bar{f}(x) = \mathfrak{A}_x(z, \mathcal{P}_x^\perp \partial \bar{f}(x))$. Observe in particular that $\mathcal{P}_x \, \mathrm{D}_z \mathcal{P} \, \partial \bar{f}(x)$ depends on $\partial \bar{f}(x)$ only through is normal component $\mathcal{P}_x^\perp \partial \bar{f}(x)$. In summary we have obtained the expression

$$\operatorname{Hess} f(x)[z] = \mathcal{P}_x \partial^2 \bar{f}(x) z + \mathfrak{A}_x(z, \mathcal{P}_x^\perp \partial \bar{f}). \tag{10}$$

4 Projector and Weingarten map on specific manifolds

We now present formulas for the projector $\mathcal{P}$ and the Weingarten map $\mathfrak{A}$ on various specific manifolds. All the formulas provided for $\mathcal{P}$ and most—but apparently not all—of those provided for $\mathfrak{A}$ can be found in the literature.

4.1 The Stiefel manifold

The *Stiefel manifold* of orthonormal p-frames in $\mathbb{R}^n$, denoted by $\mathrm{St}(p, n)$, is the submanifold of the Euclidean space $\mathbb{R}^{n \times p}$ defined by

$$\mathrm{St}(p, n) = \{X \in \mathbb{R}^{n \times p} : X^\mathrm{T} X = I_p\},$$

where I_p stands for the identity matrix of size p. We point out that the Riemannian metric obtained on $\mathrm{St}(p,n)$ by making it a Riemannian submanifold of $\mathbb{R}^{n\times p}$ is different from the canonical metric mentioned in [8, §2.3.1]. The orthogonal projector $\mathcal{P}_X$ onto $\mathrm{T}_X\mathrm{St}(p,n)$ is given by

$$\begin{aligned}\mathcal{P}_X U &= (I - XX^{\mathrm{T}})U + X\frac{1}{2}(X^{\mathrm{T}}U - U^{\mathrm{T}}X)\\ &= U - X\frac{1}{2}(X^{\mathrm{T}}U + U^{\mathrm{T}}X);\end{aligned}$$

see, e.g., [2, §3.6.1].

Let $Z \in \mathrm{T}_X\mathcal{M}$ and $V \in \mathrm{T}_X^{\perp}\mathcal{M}$. Hence $V = XS$ with $S = S^{\mathrm{T}}$ and $Z = X_{\perp}K + X\Omega$ where $\Omega = -\Omega^{\mathrm{T}}$, K is an arbitrary $(n-p)\times p$ matrix, and $X_{\perp}$ is an orthonormal $n \times (n-p)$ matrix such that $X^{\mathrm{T}}X_{\perp} = 0$; see [2, §3.6.1] for details. We have

$$\mathcal{P}_X \mathrm{D}_Z \mathcal{P} V = \mathcal{P}_X\left(V - Z\frac{1}{2}(X^{\mathrm{T}}V + V^{\mathrm{T}}X) - X\frac{1}{2}(Z^{\mathrm{T}}V + V^{\mathrm{T}}Z)\right).$$

Since V and $X\frac{1}{2}(Z^{\mathrm{T}}V + V^{\mathrm{T}}Z)$ belong to the normal space $\mathrm{T}_X^{\perp}\mathrm{St}(p,n)$, and since $\frac{1}{2}(X^{\mathrm{T}}V + V^{\mathrm{T}}X) = S$, we are left with

$$\begin{aligned}\mathcal{P}_X \mathrm{D}_Z \mathcal{P} V &= -\mathcal{P}_X ZS\\ &= -ZS + X\frac{1}{2}(X^{\mathrm{T}}ZS + SZ^{\mathrm{T}}X)\\ &= -ZS + \frac{1}{2}X\Omega S - \frac{1}{2}XS\Omega\\ &= -ZX^{\mathrm{T}}V - \frac{1}{2}XZ^{\mathrm{T}}V - \frac{1}{2}VX^{\mathrm{T}}Z\\ &= -ZX^{\mathrm{T}}V - X\frac{1}{2}(Z^{\mathrm{T}}V + V^{\mathrm{T}}Z).\end{aligned}$$

In summary, for all $Z \in \mathrm{T}_X\mathcal{M}$ and $V \in \mathrm{T}_X^{\perp}\mathcal{M}$, we have

$$\mathfrak{A}_X(Z,V) = -ZX^{\mathrm{T}}V - X\frac{1}{2}(Z^{\mathrm{T}}V + V^{\mathrm{T}}Z).$$

An equivalent formula can be found in [11, §4.1].

4.2 The sphere

The unit sphere S^{n-1} is the Stiefel manifold $\mathrm{St}(p,n)$ with $p = 1$. The orthogonal projector $\mathcal{P}_x$ onto the tangent space reduces to

$$\mathcal{P}_x u = (I - xx^{\mathrm{T}})u = u - xx^{\mathrm{T}}u,$$

and the Weingarten map reduces to

$$\mathfrak{A}_x(z,v) = -zx^{\mathrm{T}}v.$$

4.3 The orthogonal group

The orthogonal group $\mathrm{O}(n)$ is the Stiefel manifold $\mathrm{St}(p,n)$ with $p = n$. The orthogonal projector $\mathcal{P}_X$ onto the tangent space reduces to

$$\mathcal{P}_X U = X\frac{1}{2}(X^{\mathrm{T}}U - U^{\mathrm{T}}X),$$

and the Weingarten map reduces to

$$\mathfrak{A}_X(Z,V) = -X\frac{1}{2}(V^{\mathrm{T}}Z - Z^{\mathrm{T}}V).$$

4.4 The Grassmann manifold

Let $\mathrm{Gr}_{m,n}$ denote the Grassmann manifold of m-dimensional subspaces of $\mathbb{R}^n$, viewed as the set of rank-m orthogonal projectors in R^n, i.e.,

$$\mathrm{Gr}_{m,n} = \{X \in \mathbb{R}^{n\times n} : X^{\mathrm{T}} = X, X^2 = X, \mathrm{tr}X = n\}.$$

Then, from [10, Prop. 2.1], we have that $\mathcal{P}_X = \mathrm{ad}_X^2$ with $\mathrm{ad}_X A := [X,A] := XA - AX$ and $\mathrm{ad}_X^2 := \mathrm{ad}_X \circ \mathrm{ad}_X$. It follows that, for all $Z \in \mathrm{T}_X\mathrm{Gr}_{m,n}$ and all $V \in \mathrm{T}_X^{\perp}\mathrm{Gr}_{m,n}$, it holds that

$$\begin{aligned}
\mathcal{P}_X\,\mathrm{D}_Z\mathcal{P}\,V &= \mathrm{ad}_X^2\,(\mathrm{ad}_Z\mathrm{ad}_X V + \mathrm{ad}_X\mathrm{ad}_Z V) \\
&= \mathrm{ad}_X^2\mathrm{ad}_Z\mathrm{ad}_X V + \mathrm{ad}_X\mathrm{ad}_Z V \\
&= \mathrm{ad}_X\mathrm{ad}_Z V \\
&= -\mathrm{ad}_X\mathrm{ad}_V Z,
\end{aligned}$$

where $\mathrm{ad}_A B := [A,B] := AB - BA$. One recovers from (10) the Hessian formula of [10, (2.109)].

4.5 The fixed-rank manifold

Let $\mathcal{M}_p(m\times n)$ denote the set of all $m\times n$ matrices of rank p. This is a submanifold of $\mathbb{R}^{m\times n}$ of dimension $(m+n-p)p$; see [14, Example 8.14]. Let $X \in \mathcal{M}_p(m\times n)$ and, without loss of generality, let $X = U\Sigma V^T$ with $U \in \mathrm{St}(p,m)$ and $V \in \mathrm{St}(p,n)$. The projector $\mathcal{P}_X$ onto $\mathrm{T}_X\mathcal{M}_p(m\times n)$ is given by [20, §2.1]

$$\mathcal{P}_X W = \mathrm{P}_U W \mathrm{P}_V + \mathrm{P}_U^{\perp} W \mathrm{P}_V + \mathrm{P}_U W \mathrm{P}_V^{\perp} = W\mathrm{P}_V + \mathrm{P}_U W - \mathrm{P}_U W \mathrm{P}_V,$$

where $\mathrm{P}_U := UU^{\mathrm{T}}$ and $\mathrm{P}_U^{\perp} := I - \mathrm{P}_U$.

We now turn to the Weingarten map. Let $Z \in \mathrm{T}_X\mathcal{M}_p(m\times n)$. Let $\dot U \in \mathrm{T}_U\mathrm{St}(p,m)$, $\dot\Sigma$ diagonal, and $\dot V \in \mathrm{T}_V\mathrm{St}(p,n)$ be such that $Z = \mathrm{D}_{\dot U,\dot\Sigma,\dot V}(U\Sigma V^{\mathrm{T}}) = \dot U\Sigma V^{\mathrm{T}} + U\dot\Sigma V^{\mathrm{T}} + U\Sigma\dot V^{\mathrm{T}}$. We also let $\dot{\mathrm{P}}_U = \mathrm{D}_{\dot U}\mathrm{P}_U = \dot U U^{\mathrm{T}} + U\dot U^{\mathrm{T}}$, and likewise with $\dot{\mathrm{P}}_V$. Let $W \in \mathrm{T}_X^{\perp}\mathcal{M}_p(m\times n)$. We have

$$\begin{aligned}
\mathcal{P}_X\,\mathrm{D}_Z\mathcal{P}\,W &= \mathcal{P}_X\left(W\dot{\mathrm{P}}_V + \dot{\mathrm{P}}_U W - \dot{\mathrm{P}}_U W \mathrm{P}_V - \mathrm{P}_U W \dot{\mathrm{P}}_V\right) \\
&= \mathcal{P}_X\left(\mathrm{P}_U^{\perp} W \dot{\mathrm{P}}_V + \dot{P}_U W \mathrm{P}_V^{\perp}\right) \\
&= \mathrm{P}_U^{\perp} W \dot{\mathrm{P}}_V \mathrm{P}_V + \mathrm{P}_U \dot{\mathrm{P}}_U W \mathrm{P}_V^{\perp}.
\end{aligned}$$

Since $W \in \mathrm{T}_X^\perp \mathcal{M}_p(m \times n)$, we have $W = U_\perp L_W V_\perp^\mathrm{T}$ with L_W arbitrary; this follows from the expression of $\mathrm{T}_X \mathcal{M}_p(m \times n)$ in [20, §2.1]. Hence $U^T W = 0$, $\mathrm{P}_U^\perp W = W$, $WV = 0$, $W\mathrm{P}_V^\perp = W$. Using these equations, one obtains

$$\mathrm{P}_U^\perp W \dot{\mathrm{P}}_V \mathrm{P}_V = W(\dot{V}V^\mathrm{T} + V\dot{V}^\mathrm{T})\mathrm{P}_V = W\dot{V}V^\mathrm{T}\mathrm{P}_V = W\dot{V}V^\mathrm{T}.$$

Likewise, we obtain

$$\mathrm{P}_U \dot{\mathrm{P}}_U W \mathrm{P}_V^\perp = U\dot{U}^\mathrm{T} W.$$

In summary, we have

$$\mathcal{P}_X \, \mathrm{D}_Z \mathcal{P} \, W = W\dot{V}V^\mathrm{T} + U\dot{U}^\mathrm{T} W.$$

We now seek an alternate expression where only X, Z, and W appear. To this end, observe that the pseudo-inverse of X is given by $X^+ = V\Sigma^{-1}U^\mathrm{T}$. Then, recalling that $WV = 0$, we find that

$$\begin{aligned} WZ^\mathrm{T}(X^+)^\mathrm{T} &= W(\dot{V}\Sigma U^\mathrm{T} + V(\dot{\Sigma}U^\mathrm{T} + \Sigma\dot{U}^\mathrm{T}))U\Sigma^{-1}V^\mathrm{T} \\ &= W\dot{V}\Sigma U^\mathrm{T} U \Sigma^{-1} V^\mathrm{T} \\ &= W\dot{V}V^\mathrm{T}. \end{aligned}$$

Similarly, we obtain that

$$(X^+)^\mathrm{T} Z^\mathrm{T} W = U\dot{U}^\mathrm{T} W.$$

In conclusion, we have

$$\mathcal{P}_X \, \mathrm{D}_Z \mathcal{P} \, W = WZ^\mathrm{T}(X^+)^\mathrm{T} + (X^+)^\mathrm{T} Z^\mathrm{T} W.$$

It is interesting to note that this expression, combined with (10), provides an expression that allows to recover the Hessian formula found in [20, §2.3].

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