Relative torsion for representations in finite type Hilbert modules

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Abstract: Let $M$ be a closed manifold, $\rho$ a representation of $\pi_1(M)$ on an $\mathcal{A}$-Hilbert model $W$ of finite type ($\mathcal{A}$ a finite von Neumann algebra) and $\mu$ a Hermitian structure on the flat bundle $\mathcal{E} \to M$ associated to $\rho$. The relative torsion, first introduced by Carey, Mathai and Mishchenko, associates to any pair $(g, \tau)$, consisting of a Riemannian metric $g$ on $M$ and a generalized triangulation $\tau = (h, g')$, a numerical invariant, $\mathcal{R}(M, \rho, \mu, g, \tau)$.

Unlike the analytic torsion $T_{an}$, associated to $(M, \rho, \mu, g)$, or the Reidemeister torsion $T_{Reid}$, associated to $\mathcal{F} = (M, \rho, \mu, g, \tau)$, which are defined only when the pair $(M, \rho)$ is of determinant class, $\mathcal{R}$ is always defined and when $(M, \rho)$ is of determinant class is equal to the quotient $T_{an}/T_{Reid}$. The purpose of this paper is to prove the following Theorem:

**Theorem** (i) There exists a density $\alpha_{\mathcal{F}}$ on $M \setminus Cr(h)$, which is a local quantity so that if $\mu$ is parallel in a smooth neighborhood of $Cr(h)$ then $\alpha_{\mathcal{F}}$ vanishes on the neighborhood of the critical points and $\log \mathcal{R} = \int_{M \setminus Cr(h)} \alpha_{\mathcal{F}}$. (ii) If $\mu$ is parallel then $\mathcal{R} = 1$.

An exact formula for $\mathcal{R}$ is also provided. This theorem can be viewed as an extension of our result [BFKM] which says that in the case where $(M, \rho)$ is of determinant class and $\mu$ is parallel then $\mathcal{R} = 1$. 


0. Introduction and statements of the results

Let $M$ be a closed, connected manifold and $\rho : \Gamma \to \text{Hom}_A(W)$ a representation of $\Gamma := \pi_1(M)$ on an $A$-Hilbert module $W$ of finite type with $A$ a finite von Neumann algebra. Denote by $\mathcal{E} \to M$ the vector bundle associated to $M$ and $\rho$, equipped with the canonical flat connection $\nabla$. Let $\mu$ be a Hermitian structure of $E$ (not necessarily parallel with respect to the connection $\nabla$). Denote by $(\Omega(M;\mathcal{E}),d)$ the deRham complex of smooth forms with values in $\mathcal{E}$. Here $d_k : \Omega^k \to \Omega^{k+1}$ is the exterior differential determined by $\nabla$. A Riemannian metric $g$ on $M$ together with the Hermitian structure $\mu$ on $E$ allow to introduce an inner product on $\Omega^k$ and therefore determine an adjoint $d_k^*$ of $d_k$. Denote by $\Delta_k = d_k^*d_k + d_{k-1}d_{k-1}^*$ the Laplacian on $k$-forms. $\Delta_k$ admits a regularized determinant $\det \Delta_k$ in the von Neumann sense. If $(M,\rho)$ is of determinant class, these determinants do not vanish so that the analytic torsion can be defined, by

$$\log T_{an}(M,\rho,g,\mu) := 1/2 \sum q (-1)^{q+1} q \log \det \Delta_q.$$ 

These Laplacians can be used to introduce $s$– Sobolev norms on $\Omega$. Denote by $H_s(\Lambda^k(M;\mathcal{E}))$ the completion of $\Omega^k$ with respect to this norm. This leads to a
family of complexes $H_\bullet(\Lambda(M;E))$ of $\mathcal{A}$-Hilbert modules.
As in [BFKM], a generalized triangulation of $M$ is a pair $\tau = (h,g')$ with the following properties:

(T1) $h : M \to \mathbb{R}$ is a smooth Morse function which is selfindexing ($h(x) = \text{index}(x)$ for any critical point $x$ of $h$);

(T2) $g'$ is a Riemannian metric so that $-\text{grad}_y h$ satisfies the Morse-Smale condition (for any two distinct critical points $x$ and $y$ of $h$, the stable manifold $W^+_x$ and the unstable manifold $W^-_y$, with respect to $-\text{grad}_y h$, intersect transversely);

(T3) in a neighborhood of any critical point of $h$ one can introduce local coordinates such that, with $q$ denoting the index of this critical point,

$$h(x) = q - (x_1^2 + \ldots + x_q^2)/2 + (x_{q+1}^2 + \ldots + x_d^2)/2$$

and the metric $g'$ is Euclidean in these coordinates.

A generalized triangulation $\tau$ and a Hermitian structure $\mu$ determine the combinatorial Laplacians $\Delta^\text{comb}_h$ as follows: Let $p : \hat{M} \to M$ be the universal covering of $M$ and denote by $\hat{y}$ and $\hat{\tau} = (\hat{h}, \hat{g}')$ the lifts of $y$ and $\tau$ on $\hat{M}$. Denote by $Cr_q(\hat{h}) \subset \hat{M}$, resp. $Cr_q(h) \subset M$, the set of critical points of index $q$ of $\hat{h}$, resp. $h$, and let $Cr(\hat{h}) = \cup_q Cr_q(\hat{h})$. Notice that the group $\Gamma$ acts freely on $Cr_q(\hat{h})$ and the quotient set can be identified with $Cr_q(h)$. For each $\hat{x} \in Cr(\hat{h})$ choose orientations $\mathcal{O}_{\hat{x}} = (\mathcal{O}^+_\hat{x}, \mathcal{O}^-_{\hat{x}})$ for the stable and unstable manifolds $W^+_x$ and $W^-_x$ so that they are $\Gamma$-invariant and denote

$$\mathcal{O}_h := \{ \mathcal{O}_x | \hat{x} \in Cr(\hat{h}) \}.$$

To the system $(M, \rho, \mu, \tau, \mathcal{O}_h, )$, we associate a cochain complex of finite type over the von Neumann algebra $\mathcal{A}$, $\mathcal{C} = \mathcal{C}(M, \rho, \mu, \tau, \mathcal{O}_h) = \{ \mathcal{C}^q, \delta_q \}$, where $\mathcal{C}^q = \oplus_{x \in Cr_q(\hat{h})} \mathcal{E}_x$, which can be identified with the module of $\Gamma$-equivariant maps $f : Cr_q(\hat{h}) \to \mathcal{W}$, and the maps $\delta_q : \mathcal{C}^q \to \mathcal{C}^{q+1}$ are given by

$$\delta_q(f)(\hat{x}) := \sum_{\hat{y} \in Cr_q(\hat{h})} \nu_q(\hat{x}, \hat{y}) f(\hat{y})$$

where $\nu_q : Cr_q(\hat{h}) \times Cr_{q-1}(\hat{h}) \to \mathbb{Z}$ is defined by $\nu_q(\hat{x}, \hat{y}) := \text{intersection number} \ (W^+_x \cap V, W^+_y \cap V)$ with $V := \hat{h}^{-1}(q - \frac{1}{2})$. The cochain complex $\mathcal{C}(M, \rho, \mu, \tau, \mathcal{O}_h)$ depends on $\mu$ only via $\mu_x, x \in Cr(h)$. Let $\Delta^\text{comb}_q := \delta^*_q \delta_q + \delta_{q-1}^* \delta_{q-1}^*$ denote the combinatorial Laplacian. $\Delta^\text{comb}_q$ admits a regularized determinant $\det \Delta^\text{comb}_q$ in the von Neumann sense which, under the additional hypothesis of $(M, \rho)$ being of determinant class, does not vanish, and, under this hypothesis, allows...
to define the combinatorial torsion and, given a Riemannian metric, the Reide-
meister torsion. The combinatorial torsion is independent of the choice of $O_h$.
The concept of determinant class introduced in [BFKM] Definition 4.1 will be
reviewed in Appendix B.

The relative torsion is a numerical invariant associated to $F = (M, \rho, \mu, g, \tau)$.
Unlike the analytic torsion $T_{\text{an}}$, associated to $(M, \rho, \mu, g)$, or the Reidemeister
torsion $T_{\text{Reid}}$ associated to $F = (M, \rho, \mu, g, \tau)$, which are defined only when
$(M, \rho)$ is of determinant class, it is always defined. As shown in Appendix B,
there are many pairs $(M, \rho)$ which are not of determinant class. If $(M, \rho)$ is
of determinant class, then the analytic and Reidemeister torsion are defined
and the relative torsion is the quotient of these two torsions (cf (2.15)). To
explain the way we define the relative torsion, we notice that the inte-
gration on the $q$-cells of the generalized triangulation $\tau$ which are given by the unstable
manifolds of $-\text{grad}_g^* h$, defines a morphism

$$\text{Int} : (\Omega, d) \to (C, \delta),$$

i.e. $\text{Int}_q : \Omega^q \to C_q$ is an $A$-linear map so that $\delta_q \text{Int}_q = \text{Int}_{q+1} d_q$ (cf Appendix
by F. Laudenbach in [BZ]). We would like to define the relative torsion of the system $(M, \rho, \mu, g, \tau)$ as the torsion of the mapping cone defined by the integration map. Unfortunately, the torsion of this mapping cone cannot be defined
(at least in an obvious way); a first difficulty comes from the fact that the inte-
gration maps $\text{Int}_k$ do not extend to closed maps, defined on a dense domain of
$H_0(\Lambda^k(M; E))$. However, for $s$ sufficiently large, the integration morphism has
an extension $\text{Int}_s$

$$\text{Int}_s : H_s(\Lambda(M; E)) \to C$$

to a bounded morphism. We then consider the composition $g_s$

$$g_s : H_0(\Lambda(M; E)) \xrightarrow{\Delta + 1/d} H_0(\Lambda(M; E)) \xrightarrow{\text{Int}_s} C$$

and prove that $g_s$ induces an isomorphism in algebraic cohomology

$\text{Ker}(d_k)/\text{range}(d_{k-1})$ as well as in reduced cohomology $\text{Ker}(d_k)/\text{range}(d_{k-1})$

(cf Proposition 2.5).

This implies that the mapping cone $C(g_s)$, defined by $C(g_s)_k := C^{k-1} \oplus H_0
(\Lambda^k(M; E))$, and $d(g_s)_k := \begin{pmatrix} -\delta_{k-1} & g_k \end{pmatrix} \in \text{range}(d_{k-1})$

is an algebraically acyclic cochain complex (i.e. $\text{Ker}(d_s)/\text{range}(d_{s-1}) = 0$). In particular the complex $C(g_s)$
is a cochain complex of $A$-Hilbert modules (cf Lemma 1.11) whose Laplacians
$\Delta(g_s)_k$ are unbounded operators which admit a nonvanishing regularized deter-
ninant $\det \Delta(g_s)_k$ in the von Neumann sense. One of the purposes of section 1
is to establish this result.
The relative torsion $R_s$ is defined as the torsion $T(C(g_s))$ of the mapping cone $C(g_s)$,

$$\log R_s := \log T(C(g_s)) := \frac{1}{2} \sum_{k} (-1)^{k+1} \log \det(\Delta(g_s)_k).$$

In this paper (section 1), we show that $\log R_s$ is independent of $s$ (s sufficiently large) and thus provide a well defined number which we denote by $\log R$.

As first shown in [CMM] in a slightly different and less general presentation, one verifies that if $(M, \rho)$ is of determinant class, then $\log R = \log T_{an} - \log T_{Reid}$ (cf (2.15)) where $T_{an}$, resp. $T_{Reid}$, denotes the analytic torsion resp. Reidemeister torsion. The main result of [BFKM] can thus be stated as follows: When $(M, \rho)$ is of determinant class and $\mu$ is parallel then $R = 1$.

In this paper we provide exact formulae for the change of the relative torsion when one varies the Riemannian metric $g$, the Hermitian structure $\mu$, or the generalized triangulation $\tau$ (Propositions 3.1-3.3). The main result of this paper is the following:

**Theorem 0.1** (i) There exists a density $\alpha_{\mathcal{F}}$ on $M \setminus Cr(h)$, which is a local quantity so that if $\mu$ is parallel in a smooth neighborhood of $Cr(h)$ then $\alpha_{\mathcal{F}}$ vanishes on the neighborhood of the critical points and $\log R = \int_{M \setminus Cr(h)} \alpha_{\mathcal{F}}$.

(ii) If $\mu$ is parallel then $R = 1$.

Following the work of Bismut Zhang [BZ], one consider the closed 1 form $\theta(\rho, \mu) \in \Omega^1(M)$, the form $\Psi(TM, g) \in \Omega^{n-1}(TM \setminus M)$ and for two hermitian structures $\mu_1$ and $\mu_2$ (on the bundle $\mathcal{E} \to M$ induced from $\rho$) the smooth function $V(\rho, \mu_1, \mu_2) \in \Omega^0(M)$ cf Section 3. Denote by $e(M, g)$ the Euler form associated with the Riemannian metric $g$. The triangulation $\tau = (h, g')$ provides the vector field $X = -\text{grad}_g h$ which will be regarded as a smooth map $X : M \setminus Cr(h) \to TM \setminus M$.

**Proposition 0.1** If $\mu_0$ is a hermitian structure on the bundle induced by $\rho$ which is parallel in the neighborhood of $Cr(h)$, then $\theta(\rho, \mu_0)$ vanishes in the neighborhood of $Cr(h)$ and

$$\log R = -1/2 \int_{M \setminus Cr(h)} \theta(\rho, \mu_0) \wedge X^*(\Psi(TM, g)) + 1/2 \int_M V(\rho, \mu, \mu_0)e(M, g) +$$

$$+ F(\rho) \cdot \chi(M)$$

where $F(\rho)$ is a universal function defined on the space of representations of the group $\Gamma$. 

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It will be shown in [B] that the function $F$ is identically zero. The above result in the case $A = C$ implies the main result of [BZ]. The proof of Proposition 0.1 will be a straightforward application of Propositions 3.1-3.3 and Theorem 0.1 and is contained in Section 4. The proof of Theorem 0.1, contained in Section 4, uses the Witten deformation of the deRham complex, given by the differentials $d_k(t) := e^{-th}d_k e^{th}$. We consider a deformation $R(t)$ of the relative torsion $R = R(0)$, induced by the Witten deformation of the deRham complex. From many different possibilities for defining the deformation $R(t)$ we choose one for which the variation $\frac{d}{dt} \log R(t)$ can be computed. We define $R(t)$ as the torsion of the mapping cone associated to

$$(H_0(\Lambda(M; E), d(t))) \xrightarrow{\epsilon^h} (H_0(\Lambda(M; E), d)) \xrightarrow{\delta} (C, \delta),$$

which will be checked to be independent of $s$, cf Proposition 2.7 and Definition 2.8. The variation of $\log R(t)$ can be computed to be (cf Theorem 2.1)

$$(0.1) \quad \frac{d}{dt} \log R(t) = \dim E_x \cdot \int_M h e(M, g),$$

where $e(M, g)$ is the Euler form of the tangent bundle equipped with the Levi-Civita connection induced from $g$. It follows that $\log R(t)$ is given by $\log R + t \int_M h e(M, g)$.

To continue our discussion we say that a function $G : \mathbb{R} \to \mathbb{R}$ admits an asymptotic expansion for $t \to \infty$ if there exists a sequence $i_1 > i_2 > \ldots > i_{N} = 0$ and constants $(a_k)_{1 \leq k \leq N}, (b_k)_{1 \leq k \leq N}$ such that, as $t \to \infty$,

$$(0.2) \quad G(t) = \sum_{k=1}^{N} a_k t^{i_k} + \sum_{k=1}^{N} b_k t^{i_k} \log t + o(1).$$

For convenience, we denote by $FT(G(t))$ or $FT_{t=\infty}(G)$ the coefficient $a_N$ in the asymptotic expansion of $G(t)$ and refer to it as the free term of the expansion. Notice that the equality (0.1) implies that $\log R(t)$ admits an asymptotic expansion of the form (0.2) with $\log R$ as the free term.

By different considerations outlined below, we derive the existence of an asymptotic expansion for $\log R(t)$ of the form (0.2) and calculate the free term of this expansion as the integral on $M \setminus Cr(h)$ of a local density expressed in terms of $g, \mu$ and $\tau$. The proof of Theorem 0.1 will then be derived from the comparison of these two calculations. Using Witten deformation we decompose $\log R(t)$ into two parts

$$\log R(t) = \log R_{sm}(t) + \log T_{la}(t),$$

and show that each of the two parts admit an asymptotic expansion of the form (0.2) whose free terms can be computed. Precisely, we consider the Witten deformation $(\Omega(M; E), d(t))$ of the deRham complex, $d(t) = e^{-th}d e^{th}$. For $t$ sufficiently large, the deformed deRham complex can be decomposed,
\[
\left( \Omega(M, \mathcal{E}), d(t) \right) = \left( \Omega_{sm}(t), d(t) \right) \oplus \left( \Omega_{la}(t), d(t) \right),
\]
corresponding to the small and the large part of the spectrum of the deformed Laplacians \( \Delta_k(t) \). This decomposition induces the decomposition

\[
(H_0(\Lambda(M; \mathcal{E})), d(t)) = (\Omega_{sm}(t), d(t)) \oplus (H_0, la(t), d(t)).
\]

The complex \( (\Omega_{sm}(t), d(t)) \) is of finite type. Denote by \( g_{s, sm}(t) \) the restriction of \( g_s \cdot e^{th} \) to \( \Omega_{sm}(t) \), where \( e^{th} : \Omega(M, \mathcal{E}) \to \Omega(M, \mathcal{E}) \) denotes the multiplication by \( e^{th} \). The mapping cone \( C(g_{s, sm}(t)) \) is a cochain complex of \( \mathcal{A} \)-Hilbert modules of finite type which is algebraically acyclic and has a well defined torsion denoted by \( R_{sm}(t) \). As in [BFKM, section 6], one verifies that \( (H_0, la(t), d(t)) \) is algebraically acyclic and has a well defined torsion, denoted by \( T_{la}(t) \). We prove that \( \log R(t) = \log R_{sm}(t) + \log T_{la}(t) \), cf section 4 statement \( (B) \).

To prove that \( \log R_{sm}(t) \) has an asymptotic expansion, we show that \( R_{sm}(t) = T(\mathcal{C}(f(t))) \) (cf Proposition 4.1), the torsion of the mapping cone induced by

\[
f(t) : \left( \Omega_{sm}(t), d(t) \right) \xrightarrow{e^{th}} (\Omega, d) \xrightarrow{f(t)} (\mathcal{C}, \delta)
\]

and use the Witten-Helffer-Sjöstrand theory as presented in [BFKM] to prove that \( \log T(\mathcal{C}(f(t))) \) admits an asymptotic expansion of the type (0.2) and to compute its free term (Proposition 4.1). To analyze \( \log T_{la}(t) \), we proceed as in [BFK1] or [BFKM]. We derive the existence of an asymptotic expansion for \( \log T_{la}(t) \) and a closed formula for its free term from Theorem 4.2 iii). This results states the existence of an asymptotic expansion for the difference \( \log T_{la}(t) - \log \tilde{T}_{la}(t) \) where \((M, \rho, \mu, g, \tau)\) and \((\tilde{M}, \tilde{\rho}, \tilde{\mu}, \tilde{g}, \tilde{\tau})\) are two systems whose Morse functions \( h \) and \( \tilde{h} \) have the same number of critical points in each index, and provides a formula for its free term.

The paper is organized in 4 sections and two appendices.

Section 1: In subsection 1.1 we single out a class of unbounded \( \mathcal{A} \)-linear operators on \( \mathcal{A} \)-Hilbert modules ( \( \mathcal{A} \) is a von Neumann algebra with finite trace) for which the regularized determinant can be defined and in subsection 1.2 a class of complexes of \( \mathcal{A} \)-Hilbert modules for which the Laplacians are operators in the above class. Therefore the torsion of an (algebraically) acyclic complex of such type can be defined. These abstract results are needed because the mapping cone of (a regularized version of) the integration map between the deRham complex and the combinatorial complex has its components direct sums of \( \mathcal{A} \)-Hilbert modules of finite type and completions (with respect to a Sobolev norm) of spaces of smooth sections in smooth bundles of \( \mathcal{A} \)-Hilbert modules of finite type (cf. [BFKM] for definitions). We show that the mapping cone of a regularized version of the integration map is a complex of the type introduced in subsection 1.2.
Section 2: Using the results of section 1, we introduce in subsection 2.1 the notion of relative torsion $R$ and in subsection 2.2 the Witten deformation $R(t)$ of the relative torsion $R$ and calculate its variation.

Section 3: We investigate how the relative torsion $R(M, \rho, \tau, g, \mu)$ varies with respect to the Riemannian metric $g$, the Hermitian structure $\mu$ and the triangulation $\tau$.

Section 4: We prove Theorem 0.1 and Proposition 0.1.

Appendix A: For the convenience of the reader we present a proof of a slightly stronger version of a Lemma due to Carey-Mathai-Mishchenko.

Appendix B: We review the concept of determinant class and provide a simple example of a pair $(M, \rho)$, $M := S^1$ and $\rho$ a representation of $\pi_1(S^1) = \mathbb{Z}$ on $l_2(\mathbb{Z})$, which is not of determinant class. The existence of such pairs legitimates the concept of relative torsion.

Throughout the paper the notions of trace (denoted by $\text{Tr}$), dimension, determinant etc. are always understood in the von Neumann sense.

1 Operators and complexes

1.1 Operators

Let $W_1, W_2$ be $A$-Hilbert modules and $\varphi : W_1 \to W_2$ an operator. Denote its domain by $\text{domain}(\varphi) \subseteq W_1$ and its range by $\text{range}(\varphi) = \varphi\left(\text{domain}(\varphi)\right) \subseteq W_2$.

Introduce the following properties of $\varphi$.

\begin{itemize}
  \item $\text{Op}(1)$ \quad $\varphi$ is $A$-linear.
  \item $\text{Op}(2)$ \quad $\varphi$ is densely defined, i.e. $\text{domain}(\varphi) = W_1$.
  \item $\text{Op}(3)$ \quad $\varphi$ is closed (i.e. the graph $\Gamma(\varphi)$ of $\varphi$ is closed in $W_1 \times W_2$).
\end{itemize}

If, instead of $\text{Op}(3)$, $\varphi$ satisfies

\begin{itemize}
  \item $\text{Op}(3)'$ \quad $\varphi$ is closable
\end{itemize}

we consider the minimal extension of $\varphi$ and denote it again by $\varphi$.

In the sequel, we will not distinguish between property $\text{Op}(3)$ and $\text{Op}(3)'$.

An operator $\varphi$ satisfying $\text{Op}(1) - \text{Op}(3)$, admits an adjoint, $\varphi^*$ (cf. e.g. [RS, p 316]) and we can consider the nonnegative, selfadjoint operator $\varphi^* \varphi$. Functional calculus permits to define the square root $|\varphi| := (\varphi^* \varphi)^{1/2}$. Then, for any $0 < t < \infty$, the heat evolution operator $e^{-t|\varphi|}$ is bounded, nonnegative and selfadjoint. The operators $|\varphi|$ and $e^{-t|\varphi|}$ satisfy the properties $\text{Op}(1) - \text{Op}(3)$. In the sequel,
if not mentioned otherwise, we assume that the operators considered satisfy $Op(1) - Op(3)$.

Denote by $dP(\lambda) \equiv dP_{|\varphi|}(\lambda)$ the (operator valued) spectral measure associated to $|\varphi|$ defined by the orthogonal projectors $P_{|\varphi|}([0, \lambda])$ \((0 \leq \lambda \leq \infty)\)

\[
P_{|\varphi|}([0, \lambda]) = \int_{0-}^{\lambda+} dP_{|\varphi|}(\lambda).
\]

Most of the operators $\varphi$ considered in this paper will satisfy the following important property

$Op(4) \quad TrP_{|\varphi|}([a, b]) < \infty \quad (for \ any \ 0 < a \leq b < \infty)$

where

\[
(1.1) \quad P_{|\varphi|}([a, b]) := \int_{a-}^{b+} dP_{|\varphi|}(\lambda).
\]

If $\varphi$ satisfies $Op(4)$ one can define the Stiltjes measure $dF_{|\varphi|}(\lambda)$ on the half line \((0, \infty)\), given by \((0 < a < b < \infty)\)

\[
(1.2) \quad \int_{a-}^{b+} dF_{|\varphi|}(\lambda) = TrP_{|\varphi|}([a, b]).
\]

The next two properties concern the asymptotic behavior of $TrP([a, b])$ for $b \uparrow \infty$ and $a \downarrow 0$:

$Op(5) \quad \text{There exists } \alpha \geq 0 \text{ such that} \quad TrP_{|\varphi|}([1, \lambda]) = 0(\lambda^\alpha) \text{ for } \lambda \uparrow \infty$

and

$Op(6) \quad TrP_{|\varphi|}([\lambda, 1]) = 0(1) \text{ for } \lambda \downarrow 0.$

If $\varphi$ satisfies properties $Op(4)$ and $Op(6)$ one can define the spectral distribution functions, associated to $|\varphi|$, \(\lambda > 0\)

\[
(1.3) \quad F_{|\varphi|}^+(\lambda) = TrP_{|\varphi|}([0, \lambda)); \quad F_{|\varphi|}(-\infty, \lambda)) = TrP_{|\varphi|}((-\infty, \lambda)).
\]

The spectral distribution function $F_{|\varphi|}^+(\lambda)$ can be described variationally as follows, \((\lambda > 0)\)

\[
(1.4) \quad F_{|\varphi|}^+(\lambda) = \sup \{\dim L | L \subset \text{domain}(|\varphi|), \perp Ker\varphi, \text{ is an } A\text{-Hilbert submodule with } |||\varphi|(x)|| < \lambda ||x|| \ \forall x \in L \}
\]
(cf e.g. [GS], [BFKM]).

If, in addition, \( \varphi \) satisfies also \( Op(5) \), one can define the heat trace \( \theta_{|\varphi|}(t) \) associated to \( \varphi \) (excluding zero modes)

\[
(1.5) \quad \theta_{|\varphi|}(t) := \int_{0+}^{\infty} e^{-t\lambda} dF_{|\varphi|}^+(\lambda) \quad (t > 0).
\]

Using integration by parts in the Stiltjes integral (1.5) one concludes from \( Op(5) \) that

\[
(1.6) \quad \theta_{|\varphi|}(t) = 0(t^{-\alpha}) \quad (t \searrow 0).
\]

Next, let us introduce the ‘partial’ zeta function \( \zeta_{I|\varphi|}^I(s) \) associated to the heat trace \( \theta_{|\varphi|}(t) \) and defined for \( s \in \mathbb{C} \) with \( Res > \alpha \) (with \( \alpha \) given by \( Op(5) \))

\[
(1.7) \quad \zeta_{I|\varphi|}^I(s) := \frac{1}{\Gamma(s)} \int_0^{1} t^{s-1} \theta_{|\varphi|}(t) dt
\]

where \( \Gamma(s) \) denotes the gamma function. Notice that \( \zeta_{I|\varphi|}^I(s) \) is holomorphic in the halfplane \( Res > \alpha \).

The following property is needed to define the notion of regularized determinant:

\( Op(7) \) \quad \( \zeta_{I|\varphi|}^I(s) \) has an analytic continuation at \( s = 0 \).

A sufficient condition for \( Op(7) \) to hold is the existence of an asymptotic expansion of \( \theta_{|\varphi|}(t) \) near \( t = 0 \) of the form

\[
(Asy) \quad \theta_{|\varphi|} = \sum_{j=0}^{m-1} a_j t^{-\alpha_j} + a_m + R(t) \quad where \quad m \in \mathbb{Z}_{\geq 0}, \quad 0 < \alpha_{m-1} < \ldots < \alpha_0 < a_0, \ldots, a_m \in \mathbb{R} \quad and \quad R(t) \quad is \quad bounded, \quad continuous \quad function \quad with \quad R(t) = o(t^{\rho}) \quad for \quad some \quad \rho \in \mathbb{R}_{>0}.
\]

The fact that \( (Asy) \) implies \( Op(7) \) follows from the following lemma, using integration by parts.

**Lemma 1.1** Let \( f : (0,1] \to \mathbb{R} \) be a continuous function of the form

\[
f(t) = \sum_{j=0}^{m-1} a_j t^{-\alpha_j} + a_m + R(t)
\]

with \( a_0, \ldots, a_m, \alpha_0, \ldots, \alpha_{m-1} \) and \( R(t) \) as in \( (Asy) \).

Then, the holomorphic function \( \xi(x) := \frac{1}{x\Gamma(s)} \int_0^{1} t^{s-1} f(t) dt, \) defined for \( Res > \alpha_0 \), has a meromorphic continuation to the half plane \( Res > -\rho \) with \( \rho > 0 \).
as in (Asy). It has only simple poles, located at $s = \alpha_j$ $(0 \leq j \leq m-1)$. In particular, $\xi(s)$ is regular at $s = 0$ and $\xi(0) = a_m$.

Some of the operators $\varphi$ we will consider have the property that 0 is not in the spectrum, i.e.,

$$\text{Op}(8) \quad \text{There exists } \varepsilon > 0 \text{ with the property that } Tr P_\varphi([0,\varepsilon]) = 0.$$ 

If $\varphi$ satisfies the properties $\text{Op}(1) - \text{Op}(8)$, then

$$\theta_\varphi(t) = 0(e^{-t\varepsilon/2}) \text{ for } t \to \infty.$$ 

Thus $\int_1^\infty t^{s-1}\theta_\varphi(t)dt$ is an entire function of $s$ and, as a consequence,

$$\zeta_\varphi^H(s) := \frac{1}{\Gamma(s)} \int_1^\infty t^{s-1}\theta_\varphi(t)dt$$

is a holomorphic function in $s \in \mathbb{C}$ with

$$\zeta_\varphi^H(0) = 0.$$ 

(Actually for $\zeta_\varphi^H(s)$, no zeta regularization is needed (cf [BFKM], subsection 6.1).)

For operators $\varphi$ satisfying properties $\text{Op}(1) - \text{Op}(8)$, one can introduce the zeta function $\zeta_\varphi(s)$

$$\zeta_\varphi(s) := \zeta_\varphi^I(s) + \zeta_\varphi^H(s) = \frac{1}{\Gamma(s)} \int_0^\infty t^{s-1}\theta_\varphi(t)dt$$

for $\text{Res} > \alpha$ which has an analytic continuation at $s = 0$. This allows to define the volume of the operator $\varphi$, $Vol\varphi$, by

$$\log Vol(\varphi) := \log det|\varphi| := -\frac{d}{ds}|s=0 \zeta_\varphi(s).$$

**Definition 1.2**

1. An operator $\varphi : \mathcal{W}_1 \to \mathcal{W}_2$ is said to be of sF type (strong Fredholm type) if

(i) $\varphi$ satisfies $\text{Op}(1) - \text{Op}(6)$ and

(ii) $\text{dim}(\text{Ker}\varphi) := Tr P_\varphi(\{0\}) < \infty$.

2. An operator $\varphi$ is a bounded operator of trace class if

(i) $\varphi$ is bounded (hence satisfies $\text{Op}(1) - \text{Op}(3)$);
(ii) $\varphi$ satisfies $\text{Op}(4)$;
(iii) $||\varphi||_{tr} := \int_{0+}^{\infty} \lambda dF_{\varphi}(\lambda) < \infty$.

3. An operator $\varphi$ is said to be $\zeta$-regular if $\varphi$ satisfies $\text{Op}(1) - \text{Op}(7)$.

4. An operator $\varphi$ is a bounded operator of finite rank if
   (i) $\varphi$ is bounded;
   (ii) $\text{dim} (\text{range}(\varphi)) < \infty$.
   (As a consequence, $\varphi$ satisfies $\text{Op}(4) - \text{Op}(6)$ and (Asy) with $m = 0$ and $\rho = 1$ and thus, $\text{Op}(1) - \text{Op}(7)$ hold.)

Notice that an operator $\varphi : W_1 \rightarrow W_2$ of sF type might not be bounded in the case where $\text{dim} W_1 = \infty$.

**Proposition 1.3** (cf [Di]) Let $u : W_1 \rightarrow W_2$ and $v : W_2 \rightarrow W_3$ be bounded operators with $u$, respectively $v$, of trace class. Then the composition $vu$ is a bounded operator of trace class and $||vu||_{tr} \leq ||v|| ||u||_{tr}$, respectively, $||vu|| \leq ||v||_{tr} ||u||$.

As the proof of Proposition 1.3 is fairly standard, we omit it. The following result will be used in the proof of Proposition 1.5, stated below:

**Lemma 1.4** Assume that $\varphi : W \rightarrow W$ is a nonnegative, selfadjoint operator (i.e. $\varphi = |\varphi|)$ of sF type. Let $0 < a < b$ and assume that $\varepsilon > 0$ satisfies $\varepsilon < F_{\varphi}(a)$. Then one can choose a smooth function $f \in C_0^\infty (\mathbb{R}_{\geq 0}; \mathbb{R})$ such that $f(\varphi)$ is a bounded operator of finite rank (hence $f(\varphi)$ is of trace class and commutes with $\varphi$) with the following properties:

(i) $F_{\varphi + f(\varphi)}(\lambda) = 0$ for $\lambda < a$ (in particular, $\varphi + f(\varphi)$ is 1-1);
(ii) $F_{\varphi + f(\varphi)}(\lambda) \geq \varepsilon$ for $\lambda \geq a$;
(iii) $F_{\varphi + f(\varphi)}(\lambda) = F_{\varphi}(\lambda)$ for $\lambda \geq b$.

**Remark** This lemma will be applied in the case when $\varphi$ is a pseudodifferential operator. Then $\varphi$ can be chosen so that $f(\varphi)$ is a smoothing operator.

**Proof** Let $g : [0, \infty) \rightarrow \mathbb{R}$ be a smooth, increasing function defined on $[0, \infty)$ with $g(\lambda) = a$ for $\lambda \leq a$, $g(\lambda) \leq \lambda$ for $a \leq \lambda \leq b$ and $g(\lambda) = \lambda$ for $\lambda \geq b$. Let $f(\lambda) := g(\lambda) - \lambda$ and define

$$f(\varphi) := \int_0^{\infty} f(\lambda) dP_{\varphi}(\lambda).$$
Proposition 1.5

(A) If \( \varphi : W \to W \) is of sF type and \( u : W \to W \) is a bounded operator of sF type, then \( \varphi + u \) is of sF type.

(B) If, in addition, \( \varphi \) and \( \varphi + u \) are selfadjoint, nonnegative operators and \( u \) is of trace class, then there exists \( \varepsilon > 0 \) so that the difference \( \zeta_{\varphi}^1(s) - \zeta_{\varphi+u}^1(s) \), defined for \( \text{Res} > \varepsilon \), has an analytic continuation to \( \text{Res} > -\varepsilon \) and its value at \( s = 0 \) is equal to \( \dim(\text{Ker}\varphi) - \dim(\text{Ker}(\varphi + u)) \).

Remark If \( v \) is a bounded operator and \( \varphi \) and \( u \) are operators as in Proposition 1.5(B), one can, instead of \( \theta_{\varphi}(t) \) and \( \theta_{\varphi+u}(t) \), consider the function \( \theta_{\varphi,v}(t) := \text{Trve}^{-t\varphi} \left( \text{Id} - \text{P}_\varphi(\{0\}) \right) \) and similarly, \( \theta_{\varphi+u,v}(t) := \text{Trve}^{-t(\varphi+u)} \left( \text{Id} - \text{P}_{\varphi+u} \right) \). Notice that for \( v = \text{Id}, \theta_{\varphi,v}(t) = \theta_{\varphi}(t) \) (\( t > 0 \)). Both expressions, \( \zeta_{\varphi,v}^1(s) := \frac{1}{\Gamma(s)} \int_0^1 t^{s-1} \theta_{\varphi,v}(t)dt \) and \( \zeta_{\varphi+u,v}^1(s) := \frac{1}{\Gamma(s)} \int_0^1 t^{s-1} \theta_{\varphi+u,v}(t)dt \), define holomorphic functions for \( \text{Res} > 0 \) and by the same arguments as in the proof of Proposition 1.5(B) (cf below) their difference is holomorphic for \( \text{Res} > -\varepsilon \) for some \( \varepsilon > 0 \) and its value at \( s = 0 \) is \( \text{Tr}(vP_\varphi \{0\}) - \text{Tr}(vP_{\varphi+u} \{0\}) \).

Proof of Proposition 1.5

(A) Since \( \varphi \) satisfies \( \text{Op}(1) - \text{Op}(3) \) and \( u \) is bounded, \( \varphi + u \) satisfies \( \text{Op}(1) \) and \( \text{Op}(2) \) as well. One verifies in a straightforward way that the graph of \( \varphi + u \) is closed (and thus \( \text{Op}(3) \) is valid) and the null space \( \text{Ker}(\varphi + u) \) has finite (von Neumann) dimension. It remains to check that \( \text{Op}(4) \) and \( \text{Op}(5) \) hold for \( \varphi + u \). To see it, notice that, again by the variational characterization of the spectral distribution function, \( F_{\varphi+u}(\lambda) \leq F_{\varphi}(\lambda + ||u||) < \infty \) \( \forall \lambda \). Thus

\[
F_{\varphi+u}(\lambda) = 0(\lambda^\alpha) \text{ for } \lambda \nearrow \infty
\]

where \( \alpha \) is given by \( \text{Op}(5) \), satisfied by \( \varphi \), and

\[
F_{\varphi+u}(\lambda) = 0(1) \text{ for } \lambda \searrow 0
\]

as \( \varphi \) satisfies \( \text{Op}(4) \) and \( \text{Op}(5) \).

(B) First we prove (B) in the case where \( u \) is of the form \( u = f(\varphi) \) with \( f \in C^\infty([0,\infty);\mathbb{R}) \) being of compact support and such that \( \varphi + f(\varphi) \) is 1-1. We claim that \( h(t) := \theta_{\varphi+u}(t) - \theta_{\varphi}(t) \) is real analytic near \( t = 0 \) and satisfies \( h(0) = \dim(\text{Ker}\varphi) \). From Lemma 1.1 one then concludes that the difference \( \zeta_{\varphi}^1(s) - \zeta_{\varphi+f(\varphi)}^1(s) \) is well defined and holomorphic.
in $s$ for $Res > \alpha$, has an analytic continuation to $Res > -1$ and takes value $\dim(\ker \varphi)$ at $s = 0$. To prove that $h(t)$ is real analytic in $t$ near $t = 0$ and satisfies $h(0) = \dim(\ker \varphi)$ we argue as follows: Since $\varphi$ and $f(\varphi)$ commute, $e^{-t(\varphi + f(\varphi))} - e^{-t\varphi} = e^{-t\varphi}(e^{-tf(\varphi)} - 1)$. By assumption, $f$ has compact support, i.e. $\supp f \subseteq [0, K]$ for some $K > 0$. Therefore

$$f(\varphi) = \int_0^\infty f(\lambda)dP_\varphi(\lambda) = \int_0^K f(\lambda)dP_{\varphi_K}(\lambda) = f(\varphi_K)$$

where $\varphi_K := \int_0^K \lambda dP_\varphi(\lambda)$ is $\varphi$ restricted to $L := \text{range} P([0, K])$.

Using that $F_{\varphi_K}(\lambda)$ is constant for $\lambda > K$, we conclude, integrating by parts,

$$h_1(t) := \text{Tr} e^{-t\varphi_K}(e^{-tf(\varphi_K)} - 1) = \int_0^K e^{-t\lambda}(e^{-tf(\lambda)} - 1)dF_{\varphi_K}(\lambda) =
= e^{-t\lambda}(e^{-tf(\lambda)} - 1)F(\lambda)|_0^K
- t\int_0^K e^{-t\lambda}(e^{-tf(\lambda)} - 1 + e^{-tf(\lambda)}f'(\lambda))F_{\varphi_K}(\lambda)d\lambda$$

which is real analytic in $t$ and satisfies $h_1(0) = 0$. Further, one obtains

$$h_2(t) := \text{Tr}(e^{-t(\varphi + f(\varphi))}P_{\varphi + f(\varphi)}(\{0\}) - e^{-t\varphi}P_{\varphi_K}(\{0\}))
= -e^{-tf(0)}\dim(\ker(\varphi + f(\varphi))) - \dim(\ker \varphi) = - \dim(\ker \varphi)$$

which is real analytic in $t$ as well and satisfies $h_2(0) = - \dim(\ker \varphi)$. We conclude that $h(t) = h_1(t) - h_2(t)$ is real analytic in $t$ and $h(0) = \dim(\ker \varphi)$.

To prove (B) in the general case it suffices, in view of the first step and Lemma 1.4, to consider operators $\varphi$ and $u$ so that, in addition, $\varphi$ and $\varphi + u$ are 1-1 and satisfy $Op(8)$. These additional properties allow to represent $\zeta_\varphi^1(s)$ and $\zeta_{\varphi + u}^1(s)$ by a contour integral as follows: Choose $\varepsilon > 0$ so that $F_{\varphi}(\lambda) = F_{\varphi + u}(\lambda) = 0$ for $0 \leq \lambda < \varepsilon$ and consider the contour $\Gamma_{\varepsilon/2} = \Gamma_- \cup \Gamma_0 \cup \Gamma_+$ defined by

$$\Gamma_- := \{z = re^{-i\pi}|\infty > r \geq 0\}; \Gamma_0 := \{z = \frac{\varepsilon}{2}e^{i\mu}| -\pi \leq \mu \leq \pi\};
\Gamma_+ := \{z = re^{i\pi}|\varepsilon/2 \leq r < \infty\}.$$

For $\lambda \in \Gamma_{\varepsilon/2}$, $\lambda - \varphi$ and $\lambda - \varphi - u$ are both invertible and one computes

$$R(\lambda) := (\lambda - \varphi - u)^{-1} - (\lambda - \varphi)^{-1} = (\lambda - \varphi)^{-1}u(\lambda - \varphi - u)^{-1}.$$ 

As $u$ is a bounded operator of trace class we conclude by Proposition 1.3 that, for $\lambda \in \Gamma_{\varepsilon/2}$, $R(\lambda)$ is a bounded operator of trace class as well. By a standard argument one shows that for $\lambda \in \Gamma_{\varepsilon/2}$,
(1.12) \[ \| (\lambda - \varphi)^{-1} \| \leq \frac{1}{|\lambda - \varphi|} \left( \leq \frac{1}{\varepsilon} \right) \]
(1.12') \[ \| (\lambda - \varphi - u)^{-1} \| \leq \frac{1}{|\lambda - \varphi|} \left( \leq \frac{1}{\varepsilon} \right). \]

These estimates allow to represent the difference \( A(s) := \zeta_1^I \varphi(s) - \zeta_1^I \varphi + u(s) \) by the following contour integral

(1.13) \[ A(s) = \frac{1}{2\pi i} \int_{\Gamma_{\varepsilon/2}} \lambda^{-s} Tr R(\lambda) d\lambda = A_0(s) + A_+(s) + A_-(s) \]

where

(1.14) \[ A_\pm(s) = \frac{1}{2\pi i} \int_{\Gamma_{\pm}} \lambda^{-s} Tr R(\lambda) d\lambda. \]

(1.14) \[ A_0(s) = \frac{1}{2\pi i} \int_{\Gamma_0} \lambda^{-s} Tr R(\lambda) d\lambda. \]

Notice that \( A_0(s) \) is holomorphic function for \( s \in \mathbb{C} \) and \( A_\pm(s) \) are holomorphic functions in a neighborhood of \( s = 0 \) due to the fact that \( \int_{\varepsilon/2}^{\infty} \frac{1}{(x + \varepsilon)^2} dx \) is absolutely convergent for \( |s| \) sufficiently small. Moreover, \( A_0(0) = 0 \) and \( A_+(0) + A_-(0) = 0. \]

**Examples 1.6**

1. \( \varphi : \mathcal{W}_1 \to \mathcal{W}_2 \) bounded and \( \dim \mathcal{W}_1 < \infty \): then \( \varphi \) satisfies \( Op(1) - Op(7) \) and is of trace class. In fact, \( Op(6) \) follows from (Asy) which holds with \( m = 0 \) and \( \rho = 1 \). Since \( \text{Ker} \varphi \subseteq \mathcal{W}_1 \) is of finite dimension, \( \varphi \) is of \( \text{sF} \) type.

2. \( \varphi : \mathcal{W}_1 \to \mathcal{W}_2 \) is bounded and \( \dim \mathcal{W}_2 < \infty \): then the adjoint \( \varphi^* \) of \( \varphi \) is as in Example (1). Therefore \( \varphi \) satisfies \( Op(1) - Op(6) \) and (Asy) with \( m = 0, \rho = 1 \). Moreover \( \varphi \) is of trace class. However the dimension of the nullspace \( \text{Ker} \varphi \) might not be finite. Therefore, it is useful to reduce \( \varphi \) to \( \hat{\varphi} : \mathcal{W}_1/\text{Ker} \varphi \to \mathcal{W}_2 \). Then \( \hat{\varphi} \) is injective and bounded and \( \dim (\mathcal{W}_1/\text{Ker} \varphi) \) is infinite.

3. \( \varphi \) of finite rank: then the reduced map \( \hat{\varphi} : \mathcal{W}_1/\text{Ker} \varphi \to \mathcal{W}_2 \) is bounded and injective and fits either into (1) or (2).

4. Suppose \( (M,g) \) is a closed Riemann manifold and \( \mathcal{E} \to M \) is a smooth bundle of \( \mathcal{A}\)-Hilbert modules of finite type, equipped with a Hermitian structure \( \mu \) and a smooth connection \( \nabla \) so that the \( \mathcal{A} \)-action is parallel. Using \( g, \mu, \nabla \) one can define inner products \( \langle \cdot, \cdot \rangle_{s} \) of Sobolev type on the space of smooth sections on \( \mathcal{E}, C^\infty(\mathcal{E}) \). (For \( s = 0 \), the connection \( \nabla \) is not needed.) The completion of \( C^\infty(\mathcal{E}) \) with respect to \( \langle \cdot, \cdot \rangle_{s} \) is a Hilbert space denoted by \( H_s(\mathcal{E}) \). Different choices of \( g, \mu, \nabla \) lead to the same topological vector spaces \( H_s(\mathcal{E}) \), with different inner products, but equivalent norms.
A pseudodifferential operator \((\Psi DO)\) of order \(d\) induces operators \(A : H_s(E) \to H_{s'}(E)\) which are bounded if \(s' \leq s - d\). The operator \((\Delta + id)^{-s'/2}A(\Delta + id)^{s'/2} : L_2(E) \to L_2(E)\) has a kernel of class \(C^k\) if \(s' < s - d - k - dimM\). If \(A\) is an elliptic \(\Psi DO\) of order \(d > 0\) it satisfies \(Op(1) - Op(7)\) and (Asy) (with \(m := dimM\) and \(\rho = 1/k\)) cf [BFKM] section 2. Hence \(A\) is a \(\zeta\)-regular operator of \(sF\) type.

1.2 Complexes

In this subsection we introduce the class of \(\zeta\)-regular complexes of \(sF\) type and define their algebraic and reduced cohomology. In the case where a \(\zeta\)-regular complex of \(sF\) type is algebraically acyclic or, more generally, of determinant class, one can define its torsion. We recall Milnor’s lemma which relates the torsions of a short exact sequence of complexes of finite (von Neumann) dimension. Further, within our class of complexes, we discuss the notion of a mapping cone which is a complex induced by a morphism \(f\) between two complexes and show that if \(f\) is of trace class and induces an isomorphism in algebraic cohomology then the mapping cone is algebraically acyclic. Proposition 1.15 relates, under appropriate conditions, the torsions of the mapping cones of two morphisms and their composition. The class of \(\zeta\)-regular complexes of \(sF\) type has been chosen so that it includes the mapping cone of a regularized version of the integration map between the deRham complex and the combinatorial complex, which will be discussed in section 2.

A cochain complex \(C \equiv (C_i, d_i)\) of \(A\)-Hilbert modules, 

\[
C_0 \xrightarrow{d_0} C_1 \xrightarrow{d_1} \cdots \xrightarrow{d_{N-1}} C_N
\]

consists of a finite sequence of \(A\)-Hilbert modules \(C_i(0 \leq i \leq N)\) and operators \(d_i : C_i \to C_{i+1}\), satisfying \(Op(1) - Op(3)\), with the property that \(\text{range}(d_i) \subseteq \text{domain}(d_{i+1})\) and \(d_{i+1}d_i = 0\).

Notice that the null space \(\text{Kerd}_i\) is always an \(A\)-Hilbert submodule.

**Definition 1.7** For \(0 \leq i \leq N:\)

algebraic cohomology: \(H^i(C) := \text{Kerd}_i/\text{range}(d_{i-1})\)

reduced cohomology: \(\overline{H}^i(C) := \text{Kerd}_i/\text{range}(d_{i-1})\).

We point out that the reduced cohomology \(\overline{H}^i(C)\) is an \(A\)-Hilbert module whereas the algebraic cohomology \(H^i(C)\) is, in general, not an \(A\)-Hilbert module, as \(\text{range}(d_{i-1})\) needs not to be closed. \(H^i(C)\) is always an \(A\)- module.
Given a complex \((C_i, d_i)\) we can define the adjoint operators \(d_i^* : C_{i+1} \to C_i\) and, in turn, the Laplacians \(\Delta_i\),

\[
\Delta_i = d_i^* d_i + d_{i-1} d_{i-1}^*
\]
as well as the Hodge decomposition \(C_i = \mathcal{H}_i \oplus C_i^+ \oplus C_i^-\) where

\[
\mathcal{H}_i := \text{Ker}(d_i) \cap \text{Ker}(d_{i-1}^*).
\]

\[
C_i^+ := \text{range}(d_{i-1}); C_i^- := \text{range}(d_i^*).
\]

With respect to this decomposition, the operators \(d_i, d_i^*\) and \(\Delta_i\) take the form

\[
d_i = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & d_i \\
0 & 0 & 0
\end{pmatrix};
d_i^* = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & d_i^* & 0
\end{pmatrix};
\]

\[
\Delta_i = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}.
\]

We write \(\Delta^+_i := d_{i-1} d_{i-1}^*\) and \(\Delta^-_i := d_i^* d_i\). Note that \(d_i : C_i \to C_{i+1}\) and \(d_i^* : C_{i+1} \to C_i\) are injective operators with dense image, (hence so are \(\Delta^+_i\) and \(\Delta^-_i\),) and \(\mathcal{H}_i\) is isometric to the reduced cohomology \(\overline{\mathcal{H}}(C)\).

**Definition 1.8**

(i) The cochain complex \(C = (C_i, d_i)\) is said to be of sF type if

\(\text{(CX1)}\) the operators \(d_i\) satisfy \(\text{Op}(1) - \text{Op}(6)\) (and hence, in view of the injectivity of \(d_i\), are of sF type);

\(\text{(CX2)}\) \(\dim \mathcal{H}_i < \infty\).

(ii) A complex \((C_i, d_i)\) of sF type is called \(\zeta\)-regular if, in addition,

\(\text{(CX3)}\) the operators \(d_i\) satisfy \(\text{Op}(7)\).

(iii) A complex \((C_i, d_i)\) is said to be of finite type (of finite dimension), if the \(A\)-Hilbert modules \(C_i\) are of finite type (of finite dimension) and the operators \(d_i\) are bounded.

**Remark 1** The conditions \(\text{(CX1)}\) and \(\text{(CX2)}\) are equivalent to

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the Laplacians $\Delta_i$ are of sF type

and the three properties (CX1)-(CX3) are equivalent to

the Laplacians $\Delta_i$ are $\zeta$-regular operators of sF type.

Remark 2 Assume that $\mathcal{H}_{i_0} = 0$ for some $i_0$. Using the closed graph theorem one verifies that the following statements are equivalent:

(a) $H^{i_0}(\mathcal{C}) = 0$; (b) $d^*_{i_0}$ has a bounded inverse.

Given a complex $(\mathcal{C}_i, d_i)$ of sF type, one can define the spectral distribution functions $F_i(\lambda)$ and $N_i(\lambda)$,

$$F_i(\lambda) := F_{\Delta_i}(\lambda) \left( = F_{d_i}(\lambda) \right); N_i(\lambda) := F_{\Delta_i}(\lambda).$$

Then

$$N_i(\lambda) = F_i(\lambda) + F_{i-1}(\lambda).$$

A complex $(\mathcal{C}_i, d_i)$ of sF type is said to be algebraically acyclic if $H^i(\mathcal{C}) = 0$ for $0 \leq i \leq N$.

Notice that for an acyclic complex of sF type, the spectrum of $\Delta_i$ does not contain 0. In fact, in view of Remark 2 after Definition 1.9, there exists $\varepsilon > 0$ so that $N_i(\lambda) = 0$ for $0 \leq \lambda < \varepsilon$ and the same is true for the spectral distribution function of $\Delta^+_i = d_{i-1}d^+_i$ and $\Delta^-_i = d^*_i d_i$. This allows to define the torsion $T(\mathcal{C})$ of an algebraically acyclic complex of sF type,

$$\log T(\mathcal{C}) := \frac{1}{2} \sum_q (-1)^{q+1} q \log \det \Delta_q$$

$$= \frac{1}{2} \sum_q (-1)^q \log \det \Delta^+_q = \frac{1}{2} \sum_q (-1)^{q+1} \log \det \Delta^+_q.$$

More generally, the torsion $T(\mathcal{C})$ can be defined if $(\mathcal{C}, d)$ is of determinant class, i.e.

$$\int_{0^+}^1 \log \lambda dN_i(\lambda) > -\infty \quad (0 \leq i \leq N).$$

Definition 1.9 (i) A morphism $f : \mathcal{C}_1 \to \mathcal{C}_2$ between the complexes $(\mathcal{C}^1_i, d_{1,i})$ and $(\mathcal{C}^2_i, d_{2,i})$ consists of a collection of bounded operators $f_i : \mathcal{C}^1_i \to \mathcal{C}^2_i$ so that

- $f_i(\text{domain}(d_{1,i})) \subseteq \text{domain}(d_{2,i})$; $d_{2,i} f_i = f_{i+1} d_{1,i}$ (on $\text{domain}(d_{1,i})$).
(ii) \( f \) is said to be of trace class if, in addition,

- the operators \( f_i, d^*_i, f_{i+1} \) and \( f_i d^*_i \) are bounded operators of trace class.

A morphism \( f : C^1 \to C^2 \) induces \( \mathcal{A} \)-linear maps in algebraic cohomology, \( H(f) : H^i(C^1) \to H^i(C^2) \) and bounded \( \mathcal{A} \)-linear maps on the reduced cohomology, \( \overline{H}(f)_i : \overline{H}^i(C^1) \to \overline{H}^i(C^2) \). Further, with respect to the Hodge decomposition, \( f_i \) takes the form,

\[
\begin{pmatrix}
  f_{i,11} & 0 & f_{i,13} \\
  f_{i,21} & f_{i,22} & f_{i,23} \\
  0 & 0 & f_{i,33}
\end{pmatrix}
\]

where \( f_{i,11} = \overline{H}(f)_i \).

For the convenience of the reader, we recall Milnor’s lemma which was extended for complexes of \( \mathcal{A} \)-Hilbert modules in [BFK2]. Assume that

\[
0 \to C^1 \xrightarrow{f} C^2 \xrightarrow{g} C^3 \to 0
\]

is a short exact sequence of complexes of finite dimension. It induces a long weakly exact sequence in reduced cohomology

\[
\ldots \to \overline{H}^i(C^1) \xrightarrow{\overline{H}(f)_i} \overline{H}^i(C^2) \xrightarrow{\overline{H}(g)_i} \overline{H}^i(C^3) \xrightarrow{\overline{H}(\delta)_i} \overline{H}^{i+1}(C^1) \to \ldots
\]

**Proposition 1.10** (cf [BFK2, Theorem 1.14]) If three out of the four cochain complexes \( C^1, C^2, C^3, H \) are of determinant class, then so is the fourth and one has the following equality

\[
\log T(C^2) = \log T(C^1) + \log T(C^3) + \log T(H) - \\
\sum_i (-1)^i \log T(0 \to C^1_i \to C^2_i \to C^3_i \to 0).
\]

**Remark** In [BFK2], Proposition 1.11 was only stated for complexes of finite type. By the same proof, the result remains true for complexes of finite dimension.

Given a \( \zeta \)-regular complex of sF type, \( 0 \to C_0 \xrightarrow{d_0} \cdots \xrightarrow{d_{2N}} C_{2N+1} \to 0 \), we can consider its dual. If \( C^*_0 := C_{2N+1-j} \), and \( d^*_j := d^*_j \) (adjoint of \( d_{2N-j} \)), then

\[
0 \to C^*_0 \xrightarrow{d^*_0} \cdots \xrightarrow{d^*_{2N}} C^*_0 \to 0
\]
is a $\zeta$-regular complex of sF type. Notice that $(\Delta^2_j)^*d^2_j = d^2_{N-j}d^*_{N-j}$. Thus in case $C$ is of determinant class, so is $C^\sharp$ and one obtains

$$(1.22) \quad T(C^\sharp) = T(C).$$

We end this subsection with a discussion of the mapping cone $\mathcal{C}(f) = (\mathcal{C}(f)_i; d(f)_i)$ associated to a morphism $f : \mathcal{C}^1 \rightarrow \mathcal{C}^2$ between $\zeta$-regular complexes $(\mathcal{C}^1, d_1)$ and $(\mathcal{C}^2, d_2)$ of sF type. This is a complex given by

(MC1) $\quad \mathcal{C}(f)_i := \mathcal{C}^2_{i-1} \oplus \mathcal{C}^1_i$;

(MC2) $\quad d(f)_i = \left( \begin{array}{cc} -d_{2,i-1} & f_i \\ 0 & d_{1,i} \end{array} \right).$

The Laplacians $\Delta(f)_i$ of $\mathcal{C}(f)$ can be computed,

$$(1.23) \quad \Delta(f)_i = \left( \begin{array}{cc} \Delta_{2,i-1} + f_{i-1}f^*_{i-1} & -d_{2,i-1} \cdot f_i + f_{i-1} \cdot d^*_{1,i-1} \\ -f^*_i \cdot d_{2,i-1} + d_{1,i-1} \cdot f^*_{i-1} & \Delta_{1,i} + f^*_i f_i \end{array} \right)$$

The following observation, will be used in order to introduce the relative $L^2$-torsion without making the assumption that the manifold is of determinant class:

**Lemma 1.11** (i) Let $f : \mathcal{C}^1 \rightarrow \mathcal{C}^2$ be a morphism of trace class between complexes $\mathcal{C}^1$ and $\mathcal{C}^2$ of sF type. Then the mapping cone $\mathcal{C}(f)$ is of sF type.

(ii) If, in addition, $\mathcal{C}^1$ and $\mathcal{C}^2$ are $\zeta$-regular, then $\mathcal{C}(f)$ is $\zeta$-regular.

(iii) If $\varphi : \mathcal{C}^1 \rightarrow \mathcal{C}^2$ is a morphism of trace class between $\zeta$-regular complexes of sF type which induces an isomorphism in algebraic cohomology, then the mapping cone $\mathcal{C}(f)$ is algebraically acyclic and thus has a well defined torsion $T(\mathcal{C}(f))$ (cf (1.21)).

**Proof** (i) follows from Proposition 1.5 (A) by choosing $\varphi := \left( \begin{array}{cc} \Delta_{2,i-1} & 0 \\ 0 & \Delta_{1,i} \end{array} \right)$ and

$$u_i := \Delta(f)_i - \varphi_i = \left( \begin{array}{cc} f_{i-1}f^*_{i-1} & -d^*_{2,i-1}f_i + f_{i-1}d^*_{1,i-1} \\ -f^*_i d_{2,i-1} + d_{1,i-1}f^*_{i-1} & f^*_i f_i \end{array} \right)$$

By Remark 1 after Definition 1.8, the $\varphi_i$ are operators of sF type and, by assumption, the $u_i$ are bounded operators of trace class. By Proposition 1.5, $\Delta(f)_i$ is then an operator of sF type. Apply the same Remark 1 once more to conclude that (CX1) holds. Property (CX2) of Definition 1.8 is easily verified.
By Lemma 1.11, Proof

(iii) In view of (1.21) and the statements (i) and (ii) it remains to verify that \( C(f) \) is algebraically acyclic, i.e. that \( \text{range}(d(f)_{i-1}) = \text{Ker}(d(f)_i) \). Let \((v_{i-1}, u_i) \in \text{Ker}(d(f)_i) \subseteq C^2_{i-1} \oplus C^1_i\). Then

\[-d_{2,i-1}v_{i-1} + f_{i}u_i = 0; \quad d_{1,i}u_i = 0.\]

In particular, \( f_iu_i \in \text{range}(d_{2,i-1}) \) and, as \( f \) induces an isomorphism in algebraic cohomology, \( u_i \in \text{range}(d_{1,i-1}) \), i.e. there exists \( u_{i-1} \in C^1_{i-1} \) with \( u_i = d_{1,i-1}u_{i-1} \). As \( f_{i}d_{1,i-1}u_{i-1} = d_{2,i-1}f_{i-1}u_{i-1} \), we conclude that \(-v_{i-1} + f_{i-1}u_{i-1} \in \text{Ker}d_{2,i-1}\). Using once again the assumption that \( f \) induces an isomorphism in algebraic cohomology, one sees that there exists \( v_{i-2} \in C^2_{i-2} \) and \( \hat{u}_{i-1} \in \text{Ker}d_{1,i-1} \) with \(-v_{i-1} + f_{i-1}u_{i-1} = f_{i-1}\hat{u}_{i-1} + d_{2,i-2}v_{i-2}\).

Thus

\[v_{i-1} = -d_{2,i-2}v_{i-2} + f_{i-1}(u_{i-1} - \hat{u}_{i-1})\]

and, as \( \hat{u}_{i-1} \in \text{Ker}d_{1,i-1} \)

\[u_i = d_{1,i-1}u_{i-1} = d_{1,i-1}(u_{i-1} - \hat{u}_{i-1})\]

i.e. we have shown that \((v_{i-1}, u_i) \in \text{range}(d)_{i-1}\), and therefore that \( \text{Ker}(d(f)_i) = \text{range}(d)_{i-1}\). \( \blacksquare \)

If \( f : (C, d_1) \to (C, d_2) \) is an isomorphism of complexes of finite dimension we can use Lemma 1.11 together with Milnor’s lemma to compute the torsion of the mapping cone \( C(f) \). Recall that the suspension \( \Sigma C = (\Sigma C_{i,j}d_i) \) of a complex \( C = (C_i, d_i) \) is the complex given by

\[\Sigma C_i \equiv (\Sigma C)_i := C_{i-1}(i \geq 1); \quad \Sigma C_0 := 0; \quad \Sigma d_i := -d_{i-1}(i \geq 1); \quad d_0 = 0.\]

**Proposition 1.12** Assume that \( C^j \equiv (C, d_j)\) \((j = 1, 2)\) are \( \zeta \)-regular complexes of \( sF \) type and of finite dimension. If \( f : C^1 \to C^2 \) is an isomorphism, then the mapping cone \( C(f) \) is algebraically acyclic and

\[\log T(C(f)) = \sum (-1)^j \log \text{vol}(f_j)\]

**Proof** By Lemma 1.11, \( C(f) \) is an algebraically \( \zeta \)-regular complex of \( sF \) type.

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First we treat the case where, in addition, $C^1$ (and then $C^2$ as well) is algebraically acyclic. Consider the following short exact sequence of cochain complexes

$$0 \rightarrow \Sigma(C, d_2) \xrightarrow{J} C(f) \xrightarrow{P} (C, d_1) \rightarrow 0$$

where $J$ (respectively $P$) is the canonical inclusion (canonical projection).

By Proposition 1.10, the corresponding long weakly exact sequence $H$ in reduced cohomology is of determinant class and

$$logT(C(f)) = logT(\Sigma C^2) + logT(C^1) + logT(H).$$

Notice that $H$ is given by

$$\ldots \rightarrow \overline{H}(\Sigma C) \rightarrow \overline{H}(C(f)) \rightarrow \overline{H}(C) \xrightarrow{\overline{H}(\delta)} \overline{H}^{i+1}(\Sigma C) \rightarrow \ldots$$

where the connecting homomorphism $\overline{H}(\delta)$ is given by the restriction $\overline{H}(f_i)$ of $f_i$ to $\overline{H}^{i+1}(\Sigma C) = \overline{H}(C)$ into $\overline{H}(C)$. Therefore

$$logT(H) = \sum (-1)^i log vol(\overline{H}(f_i)).$$

By Lemma 1.13 below, $logT(\Sigma C^2) = -logT(C^2)$. As $f_{i+1}d_{1,i} = d_{2,i}f_i$ we conclude that $d_{1,i} = (f_{i+1})^{-1}d_{2,i}f_i$ where $f_i^\pm : C_i^{1,\pm} \rightarrow C_i^{2,\pm}$ are the restrictions of $f_i$ to $C_i^{1,\pm}$ and are isomorphisms as well.

Thus

$$logT(C^1) = \frac{1}{2} \sum (-1)^i log det(d_{2,i}^+)$$

$$= \frac{1}{2} \sum (-1)^i log det((f_{i+1}^-)^*d_{2,i}^-((f_{i+1}^-)^{-1}(f_{i+1}^-)^{-1}d_{2,i}^-f_i^-)$$

$$= \frac{1}{2} \sum (-1)^i log det(f_{i+1}^-f_{i+1}^-)^{-1}$$

$$+ \frac{1}{2} \sum (-1)^i log det(d_{2,i}^-d_{2,i}^-)$$

$$+ \frac{1}{2} \sum (-1)^i log det(f_i^-f_i^-)$$

$$= logT(C^2) + \sum (-1)^i (log vol(f_i^+) + log vol(f_i^-)).$$

Combining the equality above yields

$$logT(C(f)) = \sum (-1)^i (log vol(f_i^+) + log vol(f_i^-))$$

$$+ \sum (-1)^i log vol(\overline{H}(f_i))$$

$$= \sum (-1)^i log vol(f_i).$$

To prove the result in general we consider a deformation $(C, d_1(\varepsilon))$ of the complex $(C, d_1)$, depending smoothly on the parameter $\varepsilon$, so that, for $\varepsilon \neq 0$, $(C, d_1(\varepsilon))$ is algebraically acyclic. The operator $d_1(\varepsilon)$ is constructed as follows: with respect to the Hodge decomposition $C_i = H_i \oplus C_i^+ \oplus C_i^-$, $d_1, d_1$ takes the form
$d_{1,i} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & d_{1,i} \\ 0 & 0 & 0 \end{pmatrix}$ where $d_{1,i} : C^{-}_{1,i} \to C^{+}_{1,i+1}$. Consider the polar decomposition of $d_{1,i}d_{1,i} = \xi_{i}, \eta_{i}$ where $\xi_{i} := d_{1,i}(d_{1,i}^{*}d_{1,i})^{-1/2} : C^{-}_{i} \to C^{+}_{i+1}$ is an isometry and $\eta_{i}$ is given by $\eta_{i} := (d_{1,i}^{*}d_{1,i})^{1/2}$. The operator $\eta_{i}$ admits a spectral decomposition; $\eta_{i} = \int_{0}^{\infty} \lambda dP_{i}(\lambda)$. Define $\eta_{i}(\varepsilon) := \int_{0}^{\infty} (\lambda + \varepsilon) dP_{i}(\lambda)$ and let $d_{1,i}(\varepsilon) := \xi_{i}\eta_{i}(\varepsilon)$. Then $d_{1,i}(\varepsilon)$ is an isomorphism and thus of determinant class. Now consider $C_{1} \equiv (C, d_{1}(\varepsilon))$ where the operator $d_{1}(\varepsilon)$, with respect to the Hodge decomposition of $(C, d_{1})$, is given by $d_{1}(\varepsilon) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & d_{1,i}(\varepsilon) \\ 0 & 0 & 0 \end{pmatrix}$. Define $(C, d_{2}(\varepsilon))$ where $d_{2,i}(\varepsilon) := f_{i+1}^{+} d_{1,i}(\varepsilon) f_{i}^{-1}$. Then, for any $\varepsilon$, $f : (C, d_{1}(\varepsilon)) \to (C, d_{2}(\varepsilon))$ is a morphism and, by the argument above, the torsion $T(C_{\varepsilon}(f))$ of the mapping cone $C_{\varepsilon}(f)$ induced by $f : (C, d_{1}(\varepsilon)) \to (C, d_{2}(\varepsilon))$ is given by, for $\varepsilon \neq 0$,

$$
\log T(C_{\varepsilon}(f)) = \sum (-1)^{q} \log \vol(f_{q})
$$

which is independent of $\varepsilon$. As $C_{\varepsilon}(f)$ is algebraically acyclic for all values of $\varepsilon$ and $\log T(C_{\varepsilon}(f))$ depends continuously on $\varepsilon$, we conclude that

$$
\log T(C(f)) = \sum (-1)^{q} \log \vol(f_{q}).
$$

**Lemma 1.13** (i) Let $C$ be a $\zeta$-regular complex of sF type. Then the mapping cone $C(id)$ is an algebraically acyclic $\zeta$-regular complex of sF type and satisfies $\log T(C(id)) = 0$.

(ii) If $C$ is an algebraically acyclic, $\zeta$-regular complex of sF type, then so is $\Sigma C$ and satisfies

$$
\log T(\Sigma C) = -\log T(C).
$$

**Proof** (i) By Lemma 1.11, $C(id)$ is an algebraically acyclic $\zeta$-regular complex of sF type. Use Lemma 2.4 to conclude that

$$
\log T(C(id)) = \frac{1}{2} \sum (-1)^{q+1} \log \det(\Delta_{q} + id) = 0.
$$

(ii) It follows from Definition 1.9 and the assumptions that $\Sigma C$ is an algebraically acyclic, $\zeta$-regular complex of sF type. Its torsion is therefore well defined, and by (1.21)
\[
\log T(\Sigma C) = \frac{1}{2} \sum (-1)^{q+1} \log \det (\Delta (\Sigma C)^{-}) = -\frac{1}{2} \sum (-1)^{q+1} \log \det (\Delta^{-}) = -\log T(C). \quad \blacksquare
\]

The following Lemma 1.14 is due to Carey, Mathai and Mishchenko [CMM]. For the convenience of the reader we include its statement. As the proof in the preliminary preprint [CMM] is somewhat incomplete, we refer the reader to Appendix A for a detailed proof. Let

\begin{equation}
(1.24) \quad 0 \to C^1 \xrightarrow{I} C \xrightarrow{P} C^2 \to 0
\end{equation}

be an exact sequence of cochain complexes of sF type where the complex \( C = (C_i, d_i) \) is given by \( C_i = C^1_i \oplus C^2_i \) and

\begin{equation}
(1.25) \quad d_i = \begin{pmatrix}
    d_{1,i} & f_i \\
    0 & d_{2,i}
\end{pmatrix}
\end{equation}

with \( f_i : C^2_i \to C^1_{i+1} \) satisfying

\begin{equation}
(1.26) \quad f_i(\text{domain}(d_{2,i})) \subseteq \text{domain}(d_{1,i+1}) \quad \text{and}
\end{equation}

\begin{equation}
(1.27) \quad f_{i+1}d_{2,i} + d_{1,i+1}f_i = 0 \quad \text{(on domain}(d_{2,i}))
\end{equation}

so that \( d_{i+1}d_i = 0 \). The morphism I [resp. P] in (1.24) denotes the canonical inclusion [resp. canonical projection].

**Lemma 1.14** ([CMM]) Assume \( C^1 \) and \( C^2 \) are \( \zeta \)-regular complexes of sF type which are algebraically acyclic and \( f_i : C^2_i \to C^1_{i+1} \) are bounded maps of trace class so that (1.26) and (1.27) are satisfied and \( d^*_i, f_i \) as well as \( f_id^*_i \) are bounded operators of trace class. Then the complex \( C \), given by (1.24) - (1.25), is an algebraically acyclic, \( \zeta \)-regular complex of sF type and

\begin{equation}
(1.28) \quad \log T(C) = \log T(C^1) + \log T(C^2).
\end{equation}

**Proof:** cf [CMM] or Appendix A.

\[1\]The first author thanks Mishchenko for kindly making the preliminary preprint available to him.
Proposition 1.15 Suppose that $C^1, C^2$ and $C^3$ are $\zeta$-regular complexes of sF type and $f_1 : C^1 \to C^2$ and $f_2 : C^2 \to C^3$ are morphisms of trace class which induce isomorphism in algebraic cohomology. Then:

(i) $f := f_2 \circ f_1$ is a morphism of trace class;
(ii) the mapping cones $C(f_1), C(f_2)$ and $C(f)$ are $\zeta$-regular complexes of sF type;
(iii) $C(f_1), C(f_2)$ and $C(f)$ are algebraically acyclic (and thus their torsions are well defined).
(iv) If, in addition, either $C^3$ (case 1) or $C^1$ (case 2) is of finite type, then
\[ \log T(C(f)) = \log T(C(f_1)) + \log T(C(f_2)). \]

Proof The proof is an application of Lemma 1.13 and Lemma 1.14.

Case 1 ($C^3$ is of finite type): Consider the diagram

\[ \begin{array}{c}
\Sigma C(id_3) \\
\downarrow I_1 \\
\Sigma C(-f_2) \xrightarrow{I_2} C(h) \xrightarrow{P_2} C(f) \to 0 \\
\downarrow P_1 \\
C(f_1) \\
\downarrow \\
0
\end{array} \]

(1.29)

where $C(f_1), C(-f_2), C(f)$ and $C(id_3)$ are mapping cones, hence $C(f_1)_i = C_{i-1}^2 \oplus C_{i}^1, C(-f_2)_i = C_{i-1}^3 \oplus C_{i}^2, C(f)_i = C_{i-1}^3 \oplus C_{i}^1$ and $C(id_3)_i = C_{i-1}^3 \oplus C_{i}^3$. The morphism $h : C(f_1) \to C(id_3)$, is given by the operators $h_i : C_{i-1}^2 \oplus C_{i}^1 \to C_{i-1}^3 \oplus C_{i}^3$,

\[ h_i := \begin{pmatrix}
 f_{2,i-1} & 0 \\
 0 & f_i
\end{pmatrix}, \]

(1.30)

One verifies that $h_i$ are bounded maps of trace class. Denote by $C(h)$ the mapping cone of $h$, hence $C(h)_i = (C_{i-2}^3 \oplus C_{i-1}^3) \oplus (C_{i-1}^2 \oplus C_{i}^1)$. Further $I_1$, respectively $I_2$, are the canonical inclusions,
\[ I_1 : \mathcal{C}_{i-2}^3 \oplus \mathcal{C}_{i-1}^3 \to (\mathcal{C}_{i-2}^3 \oplus \mathcal{C}_{i-1}^3) \oplus (\mathcal{C}_{i-1}^2 \oplus \mathcal{C}_i^1) \]

and

\[ I_2 : \mathcal{C}_{i-2}^3 \oplus \mathcal{C}_{i-1}^2 \to (\mathcal{C}_{i-2}^3 \oplus \mathcal{C}_{i-1}^3) \oplus (\mathcal{C}_{i-1}^2 \oplus \mathcal{C}_i^1) \]

whereas \( P_1 \) and \( P_2 \) denote the canonical projections on the complement of the images of \( I_1 \) resp. \( I_2 \). One verifies (cf (1.29)) that

\[ (1.31) \quad 0 \to \Sigma \mathcal{C}(id_3) \xrightarrow{I_1} \mathcal{C}(h) \xrightarrow{P_1} \mathcal{C}(f_1) \to 0 \]

and

\[ (1.32) \quad 0 \to \Sigma \mathcal{C}(-f_2) \xrightarrow{I_2} \mathcal{C}(h) \xrightarrow{P_2} \mathcal{C}(f) \to 0 \]

are short exact sequences of cochain complexes. First notice that by Proposition 1.3, \( f = f_2 \cdot f_1 \) is a morphism of trace class which proves (i).

By Lemma 1.11, \( \mathcal{C}(f_1), \mathcal{C}(f_2) \) and \( \mathcal{C}(f) \) are algebraically acyclic, \( \zeta \)-regular complexes of sF type and, by Lemma 1.13, \( \Sigma \mathcal{C}(f_1), \Sigma \mathcal{C}(f_2), \Sigma \mathcal{C}(id_3) \) are algebraically acyclic, \( \zeta \)-regular complex of sF type. We would like to apply Lemma 1.14 to (1.31) and (1.32). For this purpose, observe that, given \( h_i : \mathcal{C}(f_1)_i = \mathcal{C}_{i-1}^2 \oplus \mathcal{C}_i \to \mathcal{C}(id_3) = \mathcal{C}_{i-1}^3 \oplus \mathcal{C}_i^1, d(h)_i \) admits the following decomposition

\[
d(h)_i = \begin{pmatrix}
\frac{d(\Sigma \mathcal{C}(id_3))_i}{d(\mathcal{C}(f_1)_i)} & h_i \\
0 & d(\mathcal{C}(f_1)_i)
\end{pmatrix},
\]

\[ (1.33) \quad \begin{pmatrix}
d_{3,i-2} & -id_{3,i-1} & f_{2,i-1} & 0 \\
0 & -d_{3,i-1} & 0 & f_i \\
0 & 0 & d_{2,i-1} & f_{1,i} \\
0 & 0 & 0 & d_{1,i}
\end{pmatrix}
\]

Using this decomposition, all assumptions in Lemma 1.15 which have not yet been proved can be verified in a straightforward way.

Therefore, we can apply Lemma 1.14 to (1.31) to conclude that \( \mathcal{C}(h) \) is an algebraically acyclic, \( \zeta \)-regular complex of sF type and

\[
\log T(\mathcal{C}(h)) = \log T(\Sigma \mathcal{C}(id_3)) + \log T(\mathcal{C}(f_1)) = \log T(\mathcal{C}(f_1))
\]

where we used that, by Lemma 1.13,
\[ \log T(\Sigma C(id_3)) = -\log T(C(id_3)) = 0 \]

In order to apply Lemma 1.14 to (1.32), notice that

\[ \begin{pmatrix} d(\Sigma C(-f_2)) & \tilde{h}_i \\ 0 & d(C(f)) \end{pmatrix} = \begin{pmatrix} d_3, i - 2 & +f_2, i - 1 \\ 0 & -d_3, i - 1 \end{pmatrix} \begin{pmatrix} \tilde{h}_i \\ -d_3, i - 1 \end{pmatrix} = d(h)_i \]

(1.35)

where, in view of (1.33), \( \tilde{h}_i : C(f)_i = C^3_{i-1} \oplus C^1_i \rightarrow C^3_{i-1} \oplus C^2_i = \Sigma C(-f_2)_{i+1} \)

given by \( \tilde{h}_i = \begin{pmatrix} -id_{3, i - 1} & 0 \\ 0 & f_{1, i} \end{pmatrix} \). As \( C^3 \) is of finite type, \( id_{3, i} : C^3_i \rightarrow C^3_i \) and therefore \( \tilde{h}_i \) are bounded maps of trace class. Again one verifies that all other assumption in Lemma 1.14 are satisfied. Thus we can apply Lemma 1.14 to (1.32), to conclude that

\[ \log T(C(h)) = \log T(\Sigma C(-f_2)) + \log T(C(f)) \]

(1.36)

where for the last identity we again used Lemma 1.13. Notice that the morphism

\[ \Phi : C(f_2) \rightarrow C(-f_2), \]

given by \( \Phi_i = \begin{pmatrix} \text{Id} & 0 \\ 0 & -\text{Id} \end{pmatrix} : C^3_{i-1} \oplus C^2_i \rightarrow C^3_{i-1} \oplus C^2_i \)

is an isometry and therefore \( \log T(C(-f_2)) = \log T(C(f_2)) \). Combining this with (1.34) and (1.36) we conclude that statement (iv) in case 1 is proved.

**Case 2** \( (C^1 \text{ of finite type}) \): In view of (1.22) it suffices to consider the dual complexes, to which we can apply case 1.

**Proposition 1.16** Suppose that \( C^1, C^2 \) and \( C^3 \) are \( \zeta \)-regular complexes of \( sF \) type and \( f_1 : C^1 \rightarrow C^2, f_2 : C^2 \rightarrow C^3 \) are morphisms which induce isomorphisms in algebraic cohomology and denote by \( f \) the composition \( f := f_2 \circ f_1 \). Then the following statements hold:

(i) If \( f_1 \) is an isometry and \( f_2 \) is of trace class, then the mapping cones \( C(f_2) \) and \( C(f) \) are algebraically acyclic \( \zeta \)-regular complexes of \( sF \) type. Moreover

\[ \log T(C(f_2)) = \log T(C(f)). \]
(ii) If $f_2$ is an isometry and $f_1$ is of trace class, then $C(f_1)$ and $C(f)$ are algebraically acyclic $\zeta$-regular complexes of $sF$ type. Moreover
\[ \log T(C(f_1)) = \log T(C(f)). \]

**Proof** The assumption imply that in case (i), $C(f_2)$ and $C(f)$ are isometric whereas in case (ii), $C(f_1)$ and $C(f)$ are isometric. From this observation and Lemma 1.11 the claimed results follow.

2 Relative torsion and its Witten deformation

In subsection 2.1 we introduce the relative torsion (cf [CMM]). As already mentioned in the introduction, the relative torsion cannot be defined as the torsion of the mapping cone associated to the integration map, denoted by $\text{Int}$, as $\text{Int}$ cannot be extended to a closed morphism on $L_2(\Lambda(M;E))$. To circumvent this difficulty we consider $s > \frac{n}{2} + 1$, and the composition
\[ L_2(\Lambda(M;E)) \equiv H_0(\Lambda(M;E)) \xrightarrow{(\Delta+Id)^{-s/2}} H_s(\Lambda(M;E)) \xrightarrow{\text{Int}_s} \mathbb{C} \]
where $H_s(\Lambda^k(M;E))$ denotes the completion of the space $\Omega^k(M;E)$ of smooth $k$-forms with respect to the $s$-Sobolev norm, $\Delta_k$ denotes the $k$-Laplacian, $\text{Int}_s$ is the extension of $\text{Int}$ to $H_s(\Lambda(M;E))$ and $\mathbb{C}$ denotes the combinatorial complex associated to $E \to M, \mu$ and a generalized triangulation $\tau = (h,\theta')$. It turns out that the composition $\text{Int}_s \cdot (\Delta + Id)^{-s/2}$ is a morphism of trace class which induces an isomorphism in algebraic cohomology and, therefore, the corresponding mapping cone $C(\text{Int}_s(\Delta + Id)^{-s/2})$ is algebraically acyclic. We show that it admits a torsion, called the relative torsion $R$ associated to $E \to M, g, \mu, \tau$, and that this torsion is independent of $s > \frac{n}{2} + 1$. In the case where $E \to M$ is of determinant class (cf [BFKM]), one can show that, $\log R = \log T_{an} - \log T_{Reid}$ where $T_{an}[T_{Reid}]$ is the analytic [Reidemeister] torsion.

To prove that $\log R$ is a local quantity (in Section 4), we will use the Witten deformation of the deRham complex, given by the differentials $d_k(t) := e^{-th}d_k e^{th}$. There are different possibilities for defining the corresponding deformation $R(t)$ of the relative torsion. We chose one for which the variation $\frac{d}{dt} \log R(t)$ can be computed. By definition, $R(t)$ is the torsion of the mapping cone associated to
\[ (L_2(\Lambda(M;E)), d(t)) \xrightarrow{e^{th}} (L_2(\Lambda(M;E)), d) \xrightarrow{\text{Int}_s(\Delta + Id)^{-s/2}} \mathbb{C}. \]

We will show, Theorem 2.1 subsection 2.2 that the variation $\frac{d}{dt} \log R(t)$ is given by
\[
\frac{d}{dt} \log \mathcal{R}(t) = \dim E_x \int_M he(M, g)
\]
where \(e(M, g)\) is the Euler form of the tangent bundle equipped with the Levi-Civit\`a connection induced from \(g\).

## 2.1 Relative torsion

Let \(M\) be a closed smooth manifold, \(E \to M\) a smooth bundle of \(\mathcal{A}\)-Hilbert modules of finite type equipped with a smooth flat connection \(\nabla\), which makes the fiberwise multiplication with elements of \(\mathcal{A}\) \(\nabla\)-parallel. Unlike in [BFKM], or [BFK1] we do not restrict to the case where the Hermitian structure \(\mu\) provided by the scalar product \(\mu_x\) of the fiber \(E_x\) of \(E(x \in M)\) is \(\nabla\)-parallel.

We denote by \(E^\sharp \to M\) the dual bundle of \(E \to M\). This is a bundle of \(\mathcal{A}\)-Hilbert modules of finite type with fiber \(E^\sharp_x\), the Hilbert space dual to \(E_x\),

\[
E^\sharp_x := \left\{ f : E_x \to \mathbb{C} \mid f \text{ bounded; } \mathbb{C}-\text{linear } (f(\alpha u) = \bar{\alpha} f(u) \forall \alpha \in \mathbb{C}) \right\}
\]
equipped with an \(\mathcal{A}\)-module structure defined by

\[
(a f)(u) := f(a^* u) \quad (a \in \mathcal{A}, u \in E_x, f \in E^\sharp_x).
\]
By Riesz’ theorem, \(E^\sharp_x\) can be identified canonically with \(E_x, \theta_x : E_x \to E^\sharp_x\),

\[
\theta_x u : E_x \to \mathbb{C}, v \to \theta_x u(v) := \mu_x(u, v)
\]
and thus induces an inner product \(\mu^\sharp_x\) on \(E^\sharp_x\). As a consequence, \(\theta_x\) becomes an \(\mathcal{A}\)-linear isometry and the bundles, \(E \to M\) and \(E^\sharp \to M\) of \(\mathcal{A}\)-Hilbert modules are isomorphic. The flat connection \(\nabla = \nabla_E\) induces a flat connection \(\nabla^\sharp := \nabla_{E^\sharp}\). In general \(E \to M\) and \(E^\sharp \to M\) are not isomorphic as bundles with flat connection unless the Hermitian structure \(\mu\) is \(\nabla_E\)-parallel. Each of these connections induces a covariant differentiation,

\[
d_k \equiv d_{k, \nabla} : \Omega^k(M; E) \to \Omega^{k+1}(M; E)
\]
and

\[
d^\sharp_k \equiv d_{k, \nabla^\sharp} : \Omega^k(M; E^\sharp) \to \Omega^{k+1}(M; E^\sharp)
\]
where \(\Omega^k(M; E) := C^\infty(\Lambda^k(T^*M) \otimes E)\) and where \(\Omega^k(M; E^\sharp)\) is defined similarly. The isomorphism \(\theta\) induces a canonical isomorphism, again denoted by \(\theta\),
between $\Omega^k(M; E)$ and $\Omega^k(M; E^e)$. To simplify notation, we write $\Lambda^k(M; E)$ for the $\mathcal{A}$-Hilbert module of finite type, $\Lambda^k(M; E) := \Lambda^k(T^*M) \otimes E$.

Similarly if $\rho$ is a representation of $\gamma$ on an $\mathcal{A}$-Hilbert module $W$ one denotes by $\rho^*$ the dual representation, of $\gamma$ an an $\mathcal{A}$ Hilbert module $W^e$. While the $\mathcal{A}$ Hilbert modules $W$ and $W^e$ are isomorphic the representations $\rho$ and $\rho^*$ are not unless they are unitary representations. It is easy to check that if $\rho$ induces $E \to M$, $\Delta$ then $\rho^*$ induces $E^e \to M$, $\Delta^*$. Given a Riemannian metric $g$ on $M$, let $\mathcal{J}_{k, E} : \Lambda^k(M; E) \to \Lambda^{n-k}(M; E^e)$ (with $n = \dim M$) be the morphism of $\mathcal{A}$-Hilbert modules defined by $\mathcal{J}_{k, E} := \mathcal{J}_k \otimes \theta$ where $\mathcal{J}_k : \Lambda^k(T^*M) \to \Lambda^{n-k}(T^*M)$ is the Hodge-star operator induced by $g$.

Denote by $d^*_k : \Omega^{k+1}(M; E) \to \Omega^k(M; E)$ the operator defined by the composition

$$
(2.1) \quad d^*_k = d^*_k \otimes : (-1)^{nk-1} \mathcal{J}_{n-k, E^e} \circ d_{n-k-1, \nabla^1} \circ \mathcal{J}_{k+1, E^e}.
$$

Further we define a scalar product $\ll \cdot, \cdot \gg : \Omega^k(M; E) \times \Omega^k(M; E) \to \mathbb{C}$ given by

$$
(2.2) \quad \ll w_1, w_2 \gg := \int_M w_1 \wedge_E w_2 \ d \text{vol}_g,
$$

where $*w_2 \equiv \mathcal{J}_{k, E} w_2$ and $\wedge_E$ is defined by

$$
\Omega^k(M; E) \times \Omega^k(M; E) \xrightarrow{Id \times \mathcal{J}_{k, E}} \Omega^k(M; E) \times \Omega^{n-k}(M; E^e) \xrightarrow{\Delta^*} \Omega^n(M; E^e) \xrightarrow{\mathcal{J}_{k, E}^*} \Omega^n(M; E),
$$

$$(w_1, w_2) \mapsto (w_1, *w_2) \mapsto w_1 \wedge w_2 \mapsto w_1 \wedge w_2$$

and $ev$ is the map induced by the evaluation map $\mathcal{E}_x \otimes \mathcal{E}^*_x \to \mathbb{C}$. Notice that with respect to the inner product $\ll \cdot, \cdot \gg$, $d^*_k$ is the formal adjoint of $d_k$, i.e. for $w_1 \in \Omega^k(M; E), w_2 \in \Omega^{k+1}(M; E)$

$$
\ll w_1, d^*_k w_2 \gg = \ll d_k w_1, w_2 \gg.
$$

Introduce the Laplacians

$$
(2.3) \quad \Delta_k = d^*_k d_k + d_{k-1} d^*_{k-1} : \Omega^k(M; E) \to \Omega^k(M; E)
$$

which are second order, elliptic essentially selfadjoint nonnegative $\mathcal{A}$-linear operators. In particular, as $M$ is closed, $(Id + \Delta_k) : \Omega^k(M; E) \to \Omega^k(M; E)$ is an isomorphism of Fréchet spaces. Using functional calculus, one can define the
powers \((Id + \Delta_k)^s\) \((s \in \mathbb{R} \text{ arbitrary})\). They can be used to define a family of scalar products on \(\Omega^k(M, \mathcal{E})\) by setting

\[
\ll w_1, w_2 \gg_s := \ll (Id + \Delta_k)^{s/2} w_1, (Id + \Delta_k)^{s/2} w_2 \gg.
\]

Clearly, \(\ll \cdot, \cdot \gg_s\) depends on the Hermitian structure \(\mu\) and the Riemannian metric \(g\). As \(d_k \Delta_k = \Delta_{k+1} d_k\) and \(\Delta_k d_k^* = d_k^* \Delta_{k+1}\), \(d_k^*\) is also the adjoint of \(d_k\) with respect to the inner product \(\ll \cdot, \cdot \gg_s\). Denote by \(H_s(\Lambda^k(M; \mathcal{E}))\) the completion of \(\Omega^k(M; \mathcal{E})\) with respect to the norm induced by the scalar product \(\ll \cdot, \cdot \gg_s\). As \(M\) is supposed to be closed, one obtains a family of complexes

\[
0 \to \ldots \to H_s(\Lambda^k(M; \mathcal{E})) \xrightarrow{d_k} H_s(\Lambda^{k+1}(M; \mathcal{E})) \to \ldots \to 0
\]

which we denote by \(H_s(\Lambda(M; \mathcal{E})) \equiv (H_s(\Lambda(M; \mathcal{E})), d)\). Here \(d_k : H_s(\Lambda^k(M; \mathcal{E})) \to H_s(\Lambda^{k+1}(M; \mathcal{E}))\) is the maximal closed extension of

\[
d_k : \Omega^k(M; \mathcal{E}) \to \Omega^{k+1}(M; \mathcal{E}),
\]

its domain is \(H_{s+1}(\Lambda^k(M; \mathcal{E}))\).

As mentioned in Examples 1.6 (4), \(H_s(\Lambda(M; \mathcal{E}))\) are \(\zeta\)-regular complexes of \(s\)-F type and the morphisms

\[
(1 + \Delta_k)^{1/2} : H_s(\Lambda^k(M; \mathcal{E})) \to H_{s-1}(\Lambda^k(M; \mathcal{E}))
\]

establish an isometry between the complexes \(H_s(\Lambda(M; \mathcal{E}))\) and \(H_{s-1}(\Lambda(M; \mathcal{E}))\). The adjoint of \(d_k\) with respect to the \(L^2\)-inner product, \(d_k^* : H_s(\Lambda^{k+1}(M; \mathcal{E})) \to H_s(\Lambda^k(M; \mathcal{E}))\), is given by the maximal closed extension of \(d_k^* : \Omega^{k+1}(M; \mathcal{E}) \to \Omega^k(M; \mathcal{E})\) (which depends on \(s\)).

Consider a generalized triangulation \(\tau = (h, g', \mathcal{O}_h)\) of \(M\) (cf introduction of [BFK], also [BFKM]) where \(h : M \to \mathbb{R}\) is a Morse function, \(g'\) is a compatible Riemannian metric on \(M\) and \(\mathcal{O}_h\) is a collection of orientations of the unstable manifolds defined by \(-\text{grad}_g h\), where \(\tilde{h}\) and \(\tilde{g}'\) are lifts of \(h\) respectively \(g'\) to the universal cover of \(M\) and denote by \(\mathcal{C} \equiv (\mathcal{C}(M, \tau, \mathcal{F}), \delta)\) the finite dimensional cochain complex of \(\mathcal{A}\)-Hilbert modules associated with \(\tau\) and \(\mathcal{F} := (\mathcal{E}, \nabla, \mu)\). The \(\mathcal{A}\)-linear map \(\text{Int}_k : \Omega^k(M; \mathcal{E}) \to \mathcal{C}^k(M, \tau, \mathcal{F})\) provided by integration (cf. [BFKM]) are continuous with respect to the Fréchet topology on \(\Omega^k(M; \mathcal{E})\) and extend, for \(s > n/2\), to bounded maps

\[
\text{Int}_{k,s} : H_s(\Lambda^k(M; \mathcal{E})) \to \mathcal{C}^k(M, \tau, \mathcal{F}).
\]

Since the integration map intertwines \(d\) and \(\delta\), they induce morphisms

\[
(2.6) \quad \text{Int}_{k,s} : H_s(\Lambda^k(M; \mathcal{E})) \to \mathcal{C}^k(M, \tau, \mathcal{F}).
\]
As $C$ is a complex of finite type Hilbert modules and $\text{Int}_{k,s}$ is bounded for $s > \frac{n}{2}$, $\text{Int}_{k,s}$ is of trace class (cf Examples 1.6 (2)). For $s' \leq s$, denote by $\text{In}_{s,s,s'}$ the embedding

\begin{equation}
\text{In}_{k,s,s'} : \Omega_s(\Lambda^k(M;E)) \rightarrow \Omega_{s'}(\Lambda^k(M;E))
\end{equation}

which is a morphism of cochain complexes. For $s - s' > n$, $\text{In}_{k,s,s'}$ is of trace class.

**Proposition 2.1** (cf [CMM, section 4])

The following families of morphisms induce isomorphisms in algebraic cohomology:

(i) $(\text{Id} + \Delta)^{s/2} : H_r(\Lambda(M;E)) \rightarrow H_{r-s}(\Lambda(M;E))$ $(\forall s, r)$;

(ii) $\text{In}_{s,s,s'} : \Omega_s(\Lambda(M;E)) \rightarrow \Omega_{s'}(\Lambda(M;E))$ $(s \geq s')$;

(iii) $\text{Int}_s : \Omega_s(\Lambda(M;E)) \rightarrow C(M, \tau, \mathcal{F})$ $(s > n/2)$.

**Proof** (i) is obvious since $(\text{Id} + \Delta)^{s/2}$ is an isometric morphism.

(ii) For ease of notation, let $H_{k,s} := \Omega_s(\Lambda^k(M;E))$. Denote by $Q_k : H_{k,0} \rightarrow H_{k,0}$ the $L_2$-orthogonal spectral projector corresponding to the interval $[0, r], r > 0$ and consider its restriction to $H_{k,s}, s > 0$. Due to the ellipticity of $\Delta_k$, $Q_k \omega \in \Omega^k(M;E)$ and $Q_k(H_{k,s})$ is isomorphic to $Q_k(\Omega^k(M;E))$. As $H_{k,s} = Q_k(H_{k,s}) \oplus (\text{Id} - Q_k)(H_{k,s})$, $H_s(\Lambda(M;E))$ is the sum of two subcomplexes, $C^1 \oplus C^2$ where $C^1 := (\text{Id} - Q_k)(H_{k,s})$ and $C^2 := Q_k(H_{k,s})$. Notice that $C^2$ is algebraically acyclic by remark after (1.20). $C^1$ has the same algebraic cohomology as $H_s(\Lambda(M;E))$ and that $\text{In}_{k,s,s'} = \begin{pmatrix} \text{Id} & 0 \\ 0 & \text{In}_{k,s,s'}(C^2) \end{pmatrix}$. Therefore, $\text{In}_{s,s,s'}$ induces an isomorphism in algebraic cohomology.

(iii) We use Witten’s deformation of the deRham complex (cf [BFKM, section 5]). For $t \in \mathbb{R}$, let $d_t := e^{-ih}d_e e^{ih}$ be the deformed exterior differential where $h : M \rightarrow \mathbb{R}$ is the Morse function of a generalized triangulation $\tau = (h, g')$. For $t$ sufficiently large, the spectrum of the deformed Laplacian $\Delta_k(t)$ splits into a small part contained in the interval $[0, 1]$ and a large part, contained in an interval of the form $[Ct, \infty]$ with $C > 0$. Denote by $(\Omega^k_{sm}(M;E)(t), d(t))$ the subcomplex associated to the small part of the spectrum. In particular, $\Omega^k_{sm}(t) = \Omega^k_{sm}(M;E)(t) = Q_k(t)(H_{k,s})$ where $Q_k(t)$ denotes the orthogonal spectral projector of $\Delta_k(t)$ corresponding to the interval $[0, 1]$. As $\Delta_k(t)$ is elliptic, one concludes that $\Omega^k_{sm}(t) \equiv \Omega^k_{sm}(M;E)(t) \subseteq \Omega^k(M;E)$ and, by [BFKM, section 5], is an $\mathcal{A}$-Hilbert module of finite type. Similarly as in the proof of (ii), $H_s(\Lambda(M;E))$ is the sum of two subcomplexes, $\Omega^k_{sm}(t) \oplus H_{s,la}(t)$, where $H_{k,s,la} := (\text{Id} - Q_k(t))(H_{k,s})$. Introduce
(2.8) $f_k(t) : \Omega^k_{sm}(M; E)(t) \to C^k(M, \tau, \mathcal{F})$
given by $f_k(t) := \text{Int}_k e^{th}$. One verifies that $f(t) : (\Omega_{sm}(t), d(t)) \to (C, \delta)$ is a
morphism of cochain complexes. By the Helffer-Sjöstrand theory (cf [BFKM, section 5]), $f(t)$ is an isomorphism for $t$ sufficiently large. In particular, it
induces an isomorphism in algebraic cohomology. For $t$ sufficiently large, $H_s(\Lambda(M; E))$ can be decomposed into two subcomplexes, $C^1 \oplus C^2$ where $C^1 = (e^{th}\Omega_{sm}(t), d)$ and $C^2 = (e^{th}H_{s,la}(t), d)$. Notice that $C^2$ is algebraically acyclic and that $C^1$ has the same algebraic cohomology as $H_s(\Lambda(M; E))$. For $s > n/2$, $\text{Int}_s : H_s(\Lambda(M; E)) = C^1 \oplus C^2 \to C$
is well defined and takes the form $(f(t)e^{-th}, \text{Int}_s|_{C^2})$. Therefore $\text{Int}_s$ induces an
isomorphism in algebraic cohomology. □

Remark 2.2 For $s - s' > n + 1$ the inclusion $\text{In}_{s, s'}$ is a morphism of trace
class (cf Definition 1.9).

As $H_s(\Lambda(M; E))$ is a $\zeta$-regular complex of sF type (for any $s \in \mathbb{R}$), we conclude from Proposition 2.1 and Lemma 1.12 that the mapping cone $\mathcal{C}(\text{In}_{s, s'})$ is algebraically acyclic and thus has a well defined torsion $T(\mathcal{C}(\text{In}_{s, s'}))(s - s' > n + 1)$.

Proposition 2.3 For $s - s' > n + 1$, $\log T(\mathcal{C}(\text{In}_{s, s'})) = 0$.

Proof Recall that the mapping cone $\mathcal{C}(\text{In}_{s, s'})$ is given by
\[
\mathcal{C}(\text{In}_{s, s'})_k := H_s(\Lambda^{k-1}(M; E)) \oplus H_s(\Lambda^k(M; E));
\]
\[
d(\text{In}_{s, s'})_k = \begin{pmatrix}
-d_{k-1} & I_{k:s, s'} \\
0 & d_k
\end{pmatrix}.
\]
Therefore, by (1.23) and (2.4),
\[
(2.9) \quad \Delta(\text{In}_{s, s'})_k = \begin{pmatrix}
\Delta_{k-1} + (\text{Id} + \Delta_{k-1})^{s-s'} & 0 \\
0 & \Delta_k + (\text{Id} + \Delta_k)^{s'-s}
\end{pmatrix}
\]
Proposition 2.3 then follows from Lemma 2.4 below. □

Lemma 2.4 Assume that $(\mathcal{C}, \delta)$ is a $\zeta$-regular cochain complex of sF type. Then
\( (i) \sum_k (-1)^k \log \det (\Delta_k + Id) = 0; \)

\( (ii) \sum_k (-1)^k \log \det (\Delta_k + (Id + \Delta_k)^{s'-s}) = 0. \)

**Proof** As the two statements can be proved in the same way, we consider only the second one. With respect to the Hodge decomposition, \( \Delta_k + Id \) takes the form (cf (1.18))

\[
\Delta_k + (Id + \Delta_k)^{s'-s} = \text{diag}(Id, \Delta_k^+ + (Id + \Delta_k^+)^{s'-s}, \Delta_k^- + (Id + \Delta_k^-)^{s'-s}).
\]

where \( \Delta_k^+ := d_{k-1}d_k^* \) and \( \Delta_k^- := d_k^*d_k \) are \( \zeta \)-regular operators of \( sF \) type and

\[
\log \det (\Delta_k + (Id + \Delta_k)^{s'-s}) = \log \det (\Delta_k^+ + (Id + \Delta_k^+)^{s'-s}) + \log \det (\Delta_k^- + (Id + \Delta_k^-)^{s'-s}).
\]

As \( \Delta_k^+ \) and \( \Delta_{k-1}^- \) have the same spectral distribution function we conclude that

\[
\log \det (\Delta_k^+ + (Id + \Delta_k^+)^{s'-s}) = \log \det (\Delta_{k-1}^- + (Id + \Delta_{k-1}^-)^{s'-s}).
\]

This proves the claimed statement. \( \blacksquare \)

**Proposition 2.5** Let \( s > \frac{n}{2} + 1, \tilde{s} > s + n + 1 \) and \( p \in \mathbb{R}_{>0} \). Then

\( (i) \text{Int}_s : H_*(\Lambda(M; \mathcal{E})) \to \mathcal{C}(M, \tau, \mathcal{F}) \)

is a morphism of trace class which induces an isomorphism in algebraic cohomology. Moreover

\[
\log T(\mathcal{C}(\text{Int}_s)) = \log T(\mathcal{C}(\text{Int}s))
\]

and

\[
\log T(\mathcal{C}(\text{Int}_s)) = \log T(\mathcal{C}(\text{Int}_s(\Delta + Id)^{p/2})),
\]

with \( (\Delta + Id)^{p/2} : H_{s+p}(\Lambda(M; \mathcal{E})) \to H_s(\Lambda(M; \mathcal{E})) \)

**Proof** By Proposition 2.1, \( \text{Int}_s \) is a morphism of cochain complexes which induces an isomorphism in algebraic cohomology. We claim that \( \text{Int}_s \) is a morphism of trace class (cf Definition 1.10). As we have already observed, \( \text{Int}_{k,s} \) is an operator of trace class for \( s > n/2 \) as it is bounded and \( \mathcal{C}^k \) is a Hilbert
module of finite type. By the same reason, \( \delta_k Int_{k+1:s} \) is of trace class for \( s > n/2 \). Finally we have to verify that \( Int_{k:s}d_k^* \) is of trace class. Use that \( Int_{k:s} = Int_{k:s-1}In_{k;s,s-1} \) and that \( In_{k;s,s-1}d_k^* \) is a bounded operator to deduce from Proposition 1.3 that \( Int_{k:s}d_k^* \) is of trace class for \( s > n/2 + 1 \). Further notice that \( Int_{s} = Int_{s} \cdot In_{s,s} \) for arbitrary \( s > n + 1 \) where \( In_{s,s} \) is a morphism of trace class (Remark 2.2) which induces an isomorphism in algebraic cohomology (Proposition 2.1). From Proposition 1.15 and Proposition 2.3 we then conclude that

\[
\log T(C(Int_s)) = \log T(C(In_{s,s})) + \log T(C(Int_s))
\]

It follows from Proposition 1.3 and the fact that \( (\Delta + \text{Id})^{p/2} \) is an isometry of cochain complexes that \( Int_s(\Delta + \text{Id})^{p/2} \) is a morphism of trace class which induces an isomorphism in algebraic cohomology. Applying Lemma 1.11 and Proposition 1.16 yields formula (2.13).

We are now ready to define the relative torsion. Our definition differs slightly from the one first introduced by [CMM].

Given \( M, \mathcal{F}, g, \tau \), define \( R_s = R_s(M, \mathcal{F}, g, \tau) \),

\[
\log R_s := \log T(C(Int_s(\Delta + \text{Id})^{-s/2})) \quad (s > n/2 + 1).
\]

Notice that, by Proposition 2.5, \( \log R_s = \log T(C(Int_s)) \) and \( R_s \) is independent of \( s > n/2 + 1 \).

**Definition 2.6** The relative torsion is defined by \( R := R_s(M, \mathcal{F}, g, \tau) \).

The name of relative torsion is justified by the observation, due to [CMM], that in the case where \( E \to M \) is of determinant class - and therefore, the analytic torsion \( T_{an} \) and the Reidemeister torsion \( T_{Reid} \) are well defined (cf [BFKM]) - \( R \) is given by

\[
\log R = \log T_{an} - \log T_{Reid}
\]

To see that (2.15) hold we would like to apply Proposition 1.10 (Milnor’s Lemma). However \( H_s(\Lambda(M; \xi)) \) is not a complex of finite dimension, we therefore decompose the mapping cone \( C(Int_s) \) as follows: As shown in the proof of Proposition 2.1 (iii), \( H_s(\Lambda(M; \mathcal{E})) = C^1 \oplus C^2 \) and \( f : Int_s \circ C^1 : C^1 \to C^2 \) is a bijective morphism where \( C^2 \) is algebraically acyclic and \( C^1 \) is given by \( C^1 := (e^{th} \Omega_{s,m}(t), d) \). Notice that \( C^1 \) has the same algebraic cohomology as \( H_s(\Lambda(M; \mathcal{E})) \). Denote by \( C^3 \) the mapping cone \( C(f) \). As \( f \) is a bijective morphism, \( C^3 = C(f) \) is algebraically acyclic. As \( f \) satisfies the assumption of Lemma 1.14 one concludes that
\[
\log R = \log T(C(\text{Int}_s)) = \log T(C^3) + \log T(C^2).
\]

The term \( \log T(C^3) \) has to be analyzed further. By assumption, \((M, \rho)\) is of determinant class. Therefore \( C^1 \) is of determinant class as well. We then obtain the following short exact sequence of cochain complexes, each of them being of determinant class,

\[
0 \to \Sigma C \to C^3 \to C^1 \to 0.
\]

As \( \Sigma C, C^3 \) and \( C^1 \) are of finite dimension we can apply Proposition 1.10 to conclude that

\[
\log T(C^3) = \log T(\Sigma C) + \log T(C^1) + \log T(\mathcal{H})
\]

where \( \mathcal{H} \) denotes the long weakly exact sequence in reduced cohomology and is of determinant class. By Lemma 1.14 and the definition of the combinatorial torsion \( T_{\text{comb}} \) (cf [BFKM]), \( \log T(\Sigma C) = - \log T(C) = - \log T_{\text{comb}} \). By the definition of the analytic torsion (cf [BFKM]), \( \log T(C^1) + \log T(C^2) = \log T_{\text{an}} \). Further \( \mathcal{H} \) is given by

\[
\ldots \to \bar{H}^i(\Sigma C) \to \bar{H}^i(C^3) \to \bar{H}^i(C^1) \xrightarrow{H(\delta_i)} \bar{H}^{i+1}(\Sigma C) \to \ldots
\]

Recall that \( C^3 \) is algebraically acyclic and \( H(\delta_i) : \bar{H}^i(C^1) \to \bar{H}^i(C) \) is given by the restriction of \( \text{Int}_i \) to \( \delta_i = \ker(\Delta_i) \) and, by the definition of the metric part \( T_{\text{met}} \) of the torsion

\[
\log T(\mathcal{H}) = - \log T_{\text{met}}.
\]

Combining the various equalities above leads to (2.15).

### 2.2 Witten deformation of the relative torsion

To obtain a local formula for \( \log R \) we consider the deformed relative torsion \( R(t) \) obtained by considering the Witten deformation of the deRham complex.

Using the generalized triangulation \( \tau = (h, g', \mathcal{O}_h) \) we consider for \( s > n/2 + 1 \) the following composition \( g_s(t) \) of morphisms.

\[
(2.16) \quad (L_2(\Lambda(M; \mathcal{E})), d(t)) \xrightarrow{c^h} (L_2(\Lambda(M; \mathcal{E})), d) \xrightarrow{(\Delta + Id)^{-s/2}} (H_s(\Lambda(M; \mathcal{E})), d) \xrightarrow{\text{Int}_s} (C, \delta).
\]

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where we recall that \( d_k(t) = e^{-\text{th} d_k e^{\text{th}}} \). For \( s > n/2 + 1 \), \( \text{Int}_s \) is a morphism of trace class (cf Proposition 2.5) and thus, by Proposition 1.3, the composition \( g_s(t) \) is a morphism of trace class. Due to Proposition 2.1, \( g_s(t) \) induces an isomorphism in algebraic cohomology, hence \( \log \mathcal{T}(\mathcal{C}(g_s(t))) \) is well defined.

**Proposition 2.7** For \( s + p > s > 2n + 2 \) and \( t \in \mathbb{R} \),
\[
\log \mathcal{T}(\mathcal{C}(g_s(t))) = \log \mathcal{T}(\mathcal{C}(g_{s+p}(t))).
\]

**Proof** Using that \( \text{Int}_s = \text{Int}_{s/2} \text{Int}_{s,s/2} \), \( g_s(t) \) is given by \( g_s(t) = \text{Int}_{s/2} \alpha_s(t) \) where \( \alpha_s(t) := \text{Int}_{s,s/2}(\Delta + \text{Id})^{-s/2} \). As \( s > 2n+2 \), \( \alpha_s(t) \) (cf. Remark 2.2) and \( \text{Int}_{s/2} \) (cf. Proposition 2.5) are morphisms of trace class. By Proposition 2.1, both \( \text{Int}_{s/2} \) and \( \alpha_s(t) \) induce isomorphisms in algebraic cohomology. Therefore we can apply Proposition 1.16 to conclude that
\[
\log \mathcal{T}(\mathcal{C}(g_s(t))) = \log \mathcal{T}(\mathcal{C}(\text{Int}_{s/2})) + \log \mathcal{T}(\mathcal{C}(\alpha_s(t))).
\]

Observe that, \( \text{Int}_{s+p} \cdot (\Delta + \text{Id})^{-p/2} = (\Delta + \text{Id})^{-p/2} \cdot \text{Int}_{s,s/2}(\Delta + \text{Id})^{-s/2} \) to deduce that
\[
g_{s+p}(t) = \text{Int}_{s+p}(\Delta + \text{Id})^{-p/2} \alpha_s(t).
\]

Using the same arguments as above we can apply Proposition 1.16 to obtain
\[
\log \mathcal{T}(\mathcal{C}(g_{s+p})) = \log \mathcal{T}(\mathcal{C}(\text{Int}_{s+p/2}(\Delta + \text{Id})^{-p/2}))+ + \log \mathcal{T}(\mathcal{C}(\alpha_s)).
\]

By Proposition 2.5,
\[
\log \mathcal{T}(\mathcal{C}(\text{Int}_{s/2+p})) = \log \mathcal{T}(\mathcal{C}(\text{Int}_{s/2})).
\]

Combining (2.17)-(2.20) leads to the claimed result. \( \blacksquare \)

In view of Proposition 2.7, \( \log \mathcal{T}(\mathcal{C}(g_s(t))) \) is independent of \( s \).

**Definition 2.8** The Witten deformation \( \mathcal{R}(t) \) of the relative torsion is defined by
\[
\log \mathcal{R}(t) := \log \mathcal{T}(\mathcal{C}(g_s(t))) \quad (s > n + 2).
\]
Using the same arguments as for the verification of (2.15) one sees that, for $E \to M$ of determinant class,

\[(2.21) \quad \log R(t) = \log T_{an}(t) - \log T_{comb} - \log T_{met}(t)\]

where $T_{an}(t)$ denotes the analytic torsion of the deformed deRham complex (cf [BFKM]), $T_{comb}$ denotes again the combinatorial torsion and $\log T_{met}(t) = -\log T(H(t))$ is the torsion of the long weakly exact sequence in cohomology obtained in a similar fashion as in the case of (2.15).

Our next objective is to calculate the variation for $\log R(t)$:

**Theorem 2.1**

\[\frac{d}{dt} \log R(t) = \dim E \int_M h \cdot e(M, g)\]

where $e(M, g)$ is the Euler form of the tangent bundle equipped with the Levi-Civit\`a connection induced from $g$. In particular, $\frac{d}{dt} \log R(t)$ is a local quantity, independent of $t$ and the Hermitian structure. Moreover if $n = \dim M$ is odd, then

\[\frac{d}{dt} \log R(t) \equiv 0.\]

**Proof** For $s > n + 2$, introduce the morphism $g_s := Int_s(\Delta + Id)^{-s/2}$. Then $g_s(t) = g_te^{th}$. Observe that for all $t$, the mapping cone $G(t) := C(g_s(t))$ is a cochain complex whose $k'$th component $G_k := C(g_s(t))_k$ is independent of $t$, given by

\[(2.22) \quad G_k = C^{k-1}(M, \tau, F) \oplus L_2(\Lambda^k(M; E)).\]

With respect to the decomposition (2.22), $d_k(t) \equiv d_k^G(t) : G_k \to G_{k+1}$ takes the form

\[(2.23) \quad d_k(t) = E_{k+1}(-t)D_kE_k(t); \quad d_k(t)^* = E_k(t)D_k^*E_{k+1}(-t).\]

where

\[E_k(t) := \begin{pmatrix} 1d & 0 \\ 0 & e^{th} \end{pmatrix}, \quad D_k := \begin{pmatrix} -\delta k-1 & g_k; s \\ 0 & d_k \end{pmatrix}\]

According to Proposition 2.5 and 1.12, the mapping cone $C(g_s(t))$ is a $\zeta$-regular, algebraically acyclic cochain complex of $sF$ type. Denote by...
\[ \Delta_k(t) \equiv \Delta^G_k(t) \text{ the } k\text{-Laplacian associated to } G \equiv \mathcal{C}(g_s(t)), \]

\[ \Delta_k(t) := \Delta_k^+(t) + \Delta_k^-(t) \]

where

\[ \Delta_k^+(t) := d_{k-1}(t)d^{*}_{k-1}(t) \quad \Delta_k^-(t) := d_k(t)d_k(t). \]

With respect to the Hodge decomposition \( G_k = G_k^+(t) \oplus G_k^-(t) \),

\[ G_k^+(t) := d_k(t)G_{k-1}(t) ; \quad G_k^-(t) := d_k(t)G_{k+1}(t), \]

\( d_k(t) \) is of the form \( d_k(t) = \left( \begin{array}{cc} 0 & 0 \\ 0 & d_k(t) \end{array} \right) \) and thus \( \Delta_k^+(t) = \left( \begin{array}{cc} \Delta_k^+(t) & 0 \\ 0 & 0 \end{array} \right) \)

and \( \Delta_k^-(t) = \left( \begin{array}{cc} 0 & 0 \\ 0 & \Delta_k^-(t) \end{array} \right) \) where \( \Delta_k^+(t) := d_{k-1}(t)d^{*}_{k-1}(t) \) and \( \Delta_k^-(t) := d_k(t)d_k(t) \). As \( \mathcal{C}(g_s(t)) \) is a \( \zeta \)-regular cochain complex, the operators \( d_k(t) \), according to Definition 1.9, satisfy Op(1)-Op(7). As \( \mathcal{C}(g_s(t)) \) is algebraically acyclic, they also satisfy Op(8). (In fact, the operators \( d_k(t) \) satisfy Op(7), because the corresponding heat traces admit an asymptotic expansion of the form (Asy) (cf Lemma 1.1).)

To compute \( \frac{d}{dt} \log R(t) \) we proceed similarly as in [BFKM] where we compute \( \frac{d}{dt} \log T_{an}(t) \). According to Definition 2.8, the relative torsion \( R(t) = T(\mathcal{C}(g_s(t))) \) is given by

\[ \log R(t) = \frac{1}{2} \sum_k (-1)^{k+1} \log \det \Delta_k^+(t) \]

and

\[ \frac{d}{dt} \log \det(\Delta_k^+(t)) = F.p. z=0 Tr(\frac{d}{dt}(\Delta_k^+(t)(\Delta_k^+(t))^{-z-1}) \]

\[ = F.p. z=0 Tr(\frac{d}{dt}(E_k(t)D_{k-1}E_{k-1}(2t)D_{k-1}E_k(-t))(\Delta_k^+(t))^{-z-1}). \]

(By \( F.p. z=0 \) we denote the constant term in the Laurent expansion at \( z = 0 \) of the expression which follows it.) To simplify writing we suppress momentarily the subscript \( k \). Then
\[
\begin{align*}
\frac{d}{dt}(E(-t)DE(2t)D^*E(-t)) &= \\
= &\left(\begin{array}{cc}
0 & 0 \\
0 & -h
\end{array}\right) E(-t)DE(2t)D^*E(-t) \\
+ E(-t)D \left(\begin{array}{cc}
0 & 0 \\
0 & 2h
\end{array}\right) E(2t)D^*E(-t) \\
+ E(-t)DE(2t)D^*E(-t) \left(\begin{array}{cc}
0 & 0 \\
0 & -h
\end{array}\right).
\end{align*}
\]

(2.26)

Substituting (2.26) into (2.25) we obtain

\[
\begin{align*}
\frac{d}{dt} \log \det(\Delta + (t)) &= \\
= & F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & -h
\end{array}\right) d(t)d(t)^* (\Delta^+ - \Delta^-)^{-z-1} \\
+ & F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & 2h
\end{array}\right) d(t)^* \Delta^+ (t)^{-z-1} \\
+ & F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & -h
\end{array}\right) \Delta^+(t)^{-z-1}.
\end{align*}
\]

(2.27)

Using that \(d(t)d(t)^* \Delta^+ (t)^{-z-1} = \Delta^+ (t)^{-z}\) together with the commutativity of the trace we conclude

\[
\begin{align*}
\frac{d}{dt} \log \det(\Delta^+ (t)) &= \\
= & F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & -h
\end{array}\right) \Delta^+_k (t)^{-z} \\
+ & F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & 2h
\end{array}\right) d_{k-1}(t) \Delta^+_k (t)^{-z-1} d_{k-1}(t).
\end{align*}
\]

(2.28)

From \(d_{k-1}^* \Delta^+_k (t) = d_{k-1}^* \Delta_{k-1}(t^*)d_{k-1}(t)^* = \Delta^+_{k-1}(t)d_{k-1}(t)^*\) we conclude that

\[
d_{k-1}^* \Delta^+_k (t) = (\Delta^+_{k-1}(t))^{-z-1} \Delta^+_{k-1}(t) = \Delta^+_{k-1}(t)^{-z}
\]

and therefore, after substituting into (2.28)

\[
\begin{align*}
\frac{d}{dt} \log \det(\Delta^+_k (t)) &= \\
= & F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & -h
\end{array}\right) (\Delta^+_k (t)^{-z} - \Delta^+_{k-1}(t)^{-z}).
\end{align*}
\]

(2.29)

This leads to

\[
\begin{align*}
\frac{d}{dt} \log T(C(g_s(t))) = & \sum_k(-1)^k F.p. \sum_{z=0}(-1) \left(\begin{array}{cc}
0 & 0 \\
0 & h
\end{array}\right) \Delta_k(t)^{-z}.
\end{align*}
\]

(2.30)
Combining this together with (2.30)-(2.32), we obtain the Hermitian structure of trace class. By Proposition 1.5 and its remark, we conclude that where $\Phi_k$ associated to the undeformed deRham complex, the Riemannian metric of trace class for $s>n/2$ and $\text{Op}(7)$.

In view of the fact that the heat trace $\text{Tr} \left( \left( \begin{array}{cc} 0 & 0 \\ 0 & h \end{array} \right) e^{-\lambda \Delta_k(t)} \right)$ admits an asymptotic expansion at $\lambda = 0$ of the form (Asy) one obtains (cf Lemma 1.1 and Op(7))

$$F.p., z=0 \quad \text{Tr} \left( \left( \begin{array}{cc} 0 & 0 \\ 0 & h \end{array} \right) \Delta_k(t)^{-z} \right) =$$

$$F.p., z=0 \left( \frac{1}{\Gamma(z)} \int_0^\infty \lambda^{z-1} \text{Tr} \left( \left( \begin{array}{cc} 0 & 0 \\ 0 & h \end{array} \right) e^{-\lambda \Delta_k(t)} \right) d\lambda \right)$$

$$= F.p., z=0 \left( \frac{1}{\Gamma(z)} \int_0^1 \lambda^{z-1} \text{Tr} \left( \left( \begin{array}{cc} 0 & 0 \\ 0 & h \end{array} \right) e^{-\lambda \Delta_k(t)} \right) d\lambda \right).$$

With respect to the decomposition (2.22) of the mapping cone $\mathcal{C}(g_s(t))$, the Laplacian $\Delta_k(t) \equiv \Delta^G_k(t)$ takes the form

$$\Delta^G_k(t) = \left( \begin{array}{cc} 0 & 0 \\ 0 & \Delta_k(t) \end{array} \right) + \Phi_k(t)$$

where $\Phi_k(t) : \mathcal{G}_k \rightarrow \mathcal{G}_k$ is given by

$$\Phi_k(t) := \left( \begin{array}{c} \frac{\delta^{\text{comb}}_{k-1} + g_{k-1,s}(t)g_{k-1,s}(t)\delta_{k-1} - \delta_{k-1}^* g_{k,s}(t) + g_{k-1,s}(t) \delta_{k-1}^*}{g_{k,s}(t)^* g_{k,s}(t)} \end{array} \right).$$

As $g_{k,s}(t)$ and $g_{k,s}(t)^*$ are bounded operators of trace class for $s > \frac{n}{2} + 1$ (cf Proposition 2.5) the maps $g_{k,s}(t)\delta^*_k(t)$ and $d_k(t)g_{k,s}(t)^*$ are bounded operators of trace class for $s > n/2 + 1$ and we conclude that $\Phi_k(t)$ is a bounded operator of trace class. By Proposition 1.5 and its remark, we conclude that

$$F.p., z=0 \left( \frac{1}{\Gamma(z)} \int_0^1 \lambda^{z-1} \text{Tr} \left( \left( \begin{array}{cc} 0 & 0 \\ 0 & h \end{array} \right) e^{-\lambda \Delta^G_k(t)} \right) d\lambda \right) =$$

$$= F.p., z=0 \left( \frac{1}{\Gamma(z)} \int_0^1 \lambda^{z-1} \text{Tr} \left( h e^{-\lambda \Delta_k(t)} (\text{Id} - P_{\Delta_k(t)}(\{0\})) \right) d\lambda \right)$$

where $P_{\Delta_k(t)}(\{0\})$ denotes the orthogonal projection onto $\text{Ker} \Delta_k(t)$.

One verifies (cf [BZ, p 81]) that $e^{th} \Delta_k(t) e^{-th}$ are equal to the Laplacians $\Delta^G_k$, associated to the undeformed deRham complex, the Riemannian metric $g$ and the Hermitian structure $e^{-2th} \mu$.

Combining this together with (2.30)-(2.32), we obtain
then one can find Hermitian structure \( \mu \nabla \) by the 1-dimensional real vector bundle obtained by assigning to each point \( \theta \in U \) is flat, the map \( T \) does not depend on the choice of the curve.) Denote by

\[
\theta(\rho, \mu) \in \Omega^1(M)
\]

where we used that, as \( \Delta_k(t) = e^{-\lambda \Delta_k} \theta(t) = e^{-\lambda \Delta_k} e^t \) and \( e^t (Id - P_{\Delta_k(t)}(0)) e^{-t} = Id - P_{\Delta_k(t)}(0) \).

It is known (cf e.g. [BFKM]) that the restriction \( K_k(x; \lambda, t) \) of the Schwartz kernel of \( e^{-\lambda \Delta_k} (Id - P_{\Delta_k(t)}(0)) \) to the diagonal has an asymptotic expansion with respect to \( \lambda \) for \( \lambda \rightarrow 0 \) of the form

\[
\sum_{j \geq 0} A_{k,n-j}(t) \lambda^{n-j} e^{-j \lambda}
\]

where \( A_{k,n-j}(t) \) are smooth densities on \( M \) with values in \( \text{End}(\Lambda^k(T^* M) \otimes \mathcal{E}) \), depending on the parameter \( t \). Substituting into (2.33), and integrating with respect to \( \lambda \) leads to

\[
\frac{d}{dt} \log \mathcal{R}(t) = \sum_k (-1)^k T \circ h \circ A_{k,0}(t) = \dim \mathcal{E}_x \circ T \circ h(M, g)
\]

where \( e(M, g) \) is the Euler form, which can be proven to be equal to \( \frac{1}{\dim \mathcal{E}_x} \sum_k (-1)^k A_{k,0}(t) \). If \( \dim M \) is odd, \( e(M, g) = 0 \).

### 3 Anomalies for the relative torsion

In this section, we investigate how the relative torsion \( \mathcal{R} = \mathcal{R}(M, \rho, \tau, g, \mu) \) varies with respect to the Riemannian metric \( g \), the Hermitian structure \( \mu \) and the triangulation \( \tau \). We denote by \( \mathcal{E} \to M, \nabla \) the flat bundle associated to \( \rho \). In order to formulate the results we introduce a number of additional quantities:

**The closed 1-form** \( \theta = \theta(\rho, \mu) \in \Omega^1(M) \): Choose a finite covering \( M \) by open sets \( (U_j)_{j \in J} \), which are simply connected, and points \( x_j \in U_j \). Define \( v_j : U_j \to \mathbb{R} \) by

\[
v_j(x) := \log \det(T_{x,x_j}) = \frac{1}{2} \log \det(T_{x,x_j}^* T_{x,x_j})
\]

where \( T_{x,x_j} : (\mathcal{E}_x, \mu_x) \to (\mathcal{E}_{x_j}, \mu_{x_j}) \) denotes the parallel transport from \( \mathcal{E}_x \) to \( \mathcal{E}_{x_j} \) along any curve joining \( x \) and \( x_j \) inside \( U_j \). (As the connection \( \nabla \) of \( \mathcal{E} \to M \) is flat, the map \( T_{x,x_j} \) does not depend on the choice of the curve.) Denote by \( \theta(\rho, \mu) \) the smooth 1-form on \( M \) defined by \( \theta_j := dv_j \). Notice that if the Hermitian structure \( \mu \) is parallel with respect to the canonical flat connection \( \nabla \), then \( \theta(\mu) = 0 \).

If the representation \( \rho \) is unimodular, (i.e \( \log \det(\rho(g)) = 1 \) for any \( g \in \Gamma \)) then one can find \( \mu \) so that \( \theta(\rho, \mu) = 0 \). To see this let \( \det \mathcal{E} \to M \) denotes the 1-dimensional real vector bundle obtained by assigning to each point \( x \in M \)
the vector space $\text{det} \mathbb{R} E$, (as described in [CFM],) and let $\text{det} \nabla$ denote the induced flat connection in $\text{det} \mathbb{R} E \to M$. This is the flat bundle associated with the representation $\text{det} \mathbb{R} \rho$. The unimodularity of $\rho$ implies the existence of a parallel section $s_0$ in $\text{det} \mathbb{R} E \to M$. Take a hermitian structure $\mu$ in $E \to M$, and denote by $s$ the tautological section in $\text{det} \mathbb{R} E \to M$ induced by $\mu$. Clearly there exists a smooth nonzero function $f: M \to \mathbb{R}^+$ so that $s_0 = f \cdot s$. If $\mu$ was parallel above the open set $U$, then $f|_U = 1$. It is immediate from definition of $\theta$ that $\theta(\rho, f \cdot \mu) = 0$.

If $(\rho_i, \mu_i), i = 1, 2$ are two pairs representation and hermitian structure in the induced flat bundle, then one can verify in a straightforward manner that

$$\theta(\rho_1 \otimes \rho_2, \mu_1 \otimes \mu_2) = \theta(\rho_1, \mu_1) \otimes 1 + 1 \otimes \theta(\rho_2, \mu_2).$$

The function $V = V(\rho, \mu_1, \mu_2) \in \Omega^0(M)$: If $\mu_j, j = 1, 2$ are two Hermitian structures of $E \to M$, define the smooth function

$$V(x) := V(\rho, \mu_1, \mu_2)(x) = \log \text{vol}(Id_x : (E_x, \mu_1(x)) \to (E_x, \mu_2(x)))$$

Note that:

$$(3.1') \quad \theta(\rho, \mu_1) - \theta(\rho, \mu_2) = dV(\rho, \mu_2, \mu_1),$$

$$(3.1'') \quad V(\rho, \mu_1, \mu_2) = -V(\rho, \mu_2, \mu_1),$$

$$(3.1''') \quad V(\rho, \mu_1, \mu_3) = V(\rho, \mu_1, \mu_2) + V(\rho, \mu_2, \mu_3)).$$

The Euler form $e(M, g) \in \Omega^n(M)$: Denote by $e(M, g)$ the Euler form associated to the Levi-Civita connection on the tangent bundle $TM$.

The Chern-Simon element $[e_{CS}(M, g_1, g_2)] \in \Omega^{n-1}(M)/d\Omega^{n-2}(M)$: For two Riemannian metrics $g_1$ and $g_2$ on $M$ denote by $[e_{CS} = e_{CS}(M, g_1, g_2)]$ the Chern-Simon class, cf [BZ],p 46. Recall that

$$d(e_{CS}(M, g_1, g_2)) = e(M, g_2) - e(M, g_1)$$

and that there is a canonical construction, due to Chern-Simon, for a representative $e_{CS}$ of $[e_{CS}]$ so that for a smooth 1-parameter family $g_2(u)$ of Riemannian metrics on $M$, $e_{CS}(g_1, g_2(u))$ is a smooth 1-parameter family of $(n - 1)$ forms.

The following object will be used only is Section 4 but it is related to the previous quantities.

The form $\Psi(TM, g) \in \Omega^{n-1}(TM \setminus M)$: Let $\pi: TM \to M$ be the tangent bundle of $M$. Following Mathai-Quillen [MQ] theorem 6.4, or Bismut Zhang [BZ] Theorem 3.4, one can construct a smooth form $\Psi(TM, g) \in \Omega^{n-1}(TM \setminus M)$ so that:
\[ (3.2') \quad d\Psi(TM, g) = \pi^*(e(M, g)) \]

If \( g_1 \) and \( g_2 \) are two Riemannian metrics on \( M \) then

\[ (3.2'') \quad \Psi(TM, g_1) - \Psi(TM, g_2) = \pi^*e_{CS}(M, g_1, g_2) \]

If \( \lambda : TM \setminus M \to TM \setminus M \) denotes the multiplication by the real number \( \lambda \) then

\[ (3.2''') \quad \lambda^*(\Psi(TM, g)) = (\lambda/|\lambda|)^{n+1}\Psi(TM, g) \]

In view of the definition of \( \Psi \) cf [BZ] it is easy to check that for two Riemannian manifolds \((M_i, g_i), \; i = 1, 2\) we have

\[ (3.2''') \quad \Psi(T(M_1 \times M_2, g_1 \times g_2)) = \Psi(T(M_1, g_1) \otimes e(M_2, g_2) + e(M_1, g_1) \otimes \Psi(T(M_2, g_2)). \]

**Proposition 3.1** (Metric Anomaly of the relative torsion)

(i) \( \log R(g_2) - \log R(g_1) = -\frac{1}{2} \int_M \theta \wedge e_{CS}(g_1, g_2). \)

(ii) If \( \dim M \) is odd or \( \mu \) is a Hermitian structure parallel with respect to the canonical flat connection, the relative torsion \( R \) is independent of \( g \).

**Proposition 3.2** (Hermitian anomaly of the relative torsion)

Assume that \( \mu_2(x) = \mu_1(x), \; \forall \; x \in C^r(h), \) where \( h \) is the Morse function in \( \tau = (h, g') \).

Then:

(i) \( \log R(\mu_2) - \log R(\mu_1) = -\frac{1}{2} \int_M V(\rho, \mu_1, \mu_2)e(M, g). \)

(ii) If \( \dim M \) is odd, the relative torsion \( R \) is independent of the Hermitian structure \( \mu \).

In the case \( \mathcal{A} = \mathbb{C} \) these results were established in by Bismut Zhang, cf [BZ]. Propositions 3.1 and 3.2 will be proved at the same time. Their proof is reduced to some local index type results established in [BZ].

**Remark** Theorem 2.1. can be also derived as a special case of a (slightly more general) version of Proposition 3.2(i).

**Proof of Propositions 3.1, 3.2:** (ii) follows from (i) by noting that \( e(M, g) = 0 \) and \( e_{CS}(M, g_1, g_2) = 0 \) if \( \dim M \) is odd and that \( \theta(\mu) = 0 \) if the Hermitian structure \( \mu \) is parallel with respect to the canonical flat connection.

To prove (i), consider a smooth 1-parameter family \( g(u) \) of Riemannian metrics and a smooth 1-parameter family \( \mu(u) \) of Hermitian structures, \((-1 < u < +1)\). We want to compute \( \frac{d}{du} \log R(g(u), \mu_0) \) and \( \frac{d}{du} \log R(g_0, \mu(u)). \) We begin by analyzing \( \frac{d}{du} \log R(g(u), \mu(u)). \)
where by $\langle\cdot,\cdot\rangle$ the scalar product defined by $g(u)$ and $\mu(u)$ on $\Omega^k(M;E)$ (cf. 2.2) and by $\langle\cdot,\cdot\rangle_s(u)$ the one given by (2.4). Clearly $\langle\cdot,\cdot\rangle(u) = \langle\cdot,\cdot\rangle_0(u)$.

Denote by $\Delta_k(u):\Omega^k(M;E) \to \Omega^k(M;E)$ the Laplacian on $\Omega^k(M;E)$ induced by $g(u)$ and $\mu(u)$ and by $H_s(u)(\Lambda(M;E))$ the completion of $\Omega(M;E)$ with respect to $\langle\cdot,\cdot\rangle_s(u)$.

Consider the following commutative diagram

$$
\begin{array}{ccc}
H_0(u)(\Lambda(M;E)) & \xrightarrow{\gamma_{s+s'}(u)} & \mathcal{C}(\mathcal{R}) \\
\gamma_s\varphi_{s,s'}(u) & \nearrow & \gamma_s(0) \\
H_0(0)(\Lambda(M;E)) & & \\
\end{array}
$$

where

$$
\gamma_s(u) := \text{Int}_s(\text{Id} + \Delta(u))^{-s/2}, \quad \varphi_{s,s'}(u) := (\text{Id} + \Delta(0))^{+s'/2}(\text{Id} + \Delta(u))^{-\frac{s+s'}{2}}.
$$

We recall from Subsection 2.1 that, for $s$ and $s'$ sufficiently large, $\gamma_s(u)$ and $\varphi_{s,s'}(u)$ are morphisms of trace class. Since $\gamma_s(u)$ and $\gamma_s(0)$ induce isomorphisms in algebraic cohomology (cf. Proposition 2.5), so does $\varphi_{s,s'}(u)$.

We thus can apply Proposition 1.15 to obtain

$$
\text{(3.3)} \quad \log \mathcal{R}(g(u)) = \log \mathcal{R}(g(0)) + \log T(\mathcal{C}(\varphi_{s,s'}(u))
$$

where $\mathcal{C}(\varphi_{s,s'}(u))$ denotes the mapping cone associated to $\varphi_{s,s'}(u)$.

Since $(\text{Id} + \Delta(u))^{s/2}; H_s(u)(\Lambda(M;E)) \to H_0(u)(\Lambda(M;E))$ is an isometry, we conclude from Proposition 1.16 that

$$
\text{(3.4)} \quad T(\mathcal{C}(\varphi_{s,s'}(u))) = T(\mathcal{C}(\text{In}_{s+s',s}(u)))
$$

where

$$
\text{In}_{s+s',s}(u): H_{s+s'}(u)(\Lambda(M;E)) \to H_s(0)(\Lambda(M;E))
$$
denotes the canonical inclusion. To analyze the torsion of the mapping cone $(\mathcal{C}_u, D) := (\mathcal{C}(\text{In}_{s+s',s}(u)), d(\text{In}_{s+s',s}(u)))$, note that

$$
\text{(3.5)} \quad C_{uk} := H_s(0)(\Lambda^{k-1}(M;E)) \oplus H_{s+s'}(u)(\Lambda^k(M;E));

D_k = \begin{pmatrix}
-d_{k-1} & \text{In}_{s+s',s}(u) \\
d_k & 0
\end{pmatrix}
$$

with inner product $(\omega_1, \omega'_1, \omega_2, \omega'_2 \in \Omega^k)$

$$
\text{(3.6)} \quad \langle\langle (\omega_1, \omega_2), (\omega'_1, \omega'_2) \rangle\rangle := \langle\langle (\omega_1, \omega'_1) \rangle\rangle_s(0) + \langle\langle (\omega_2, \omega'_2) \rangle\rangle_{s+s'}(u).
$$
In order to calculate \( \frac{d}{du} \log T(\mathcal{C}(u)) \), introduce the zeroth order differential operators \( A_k(0): \Omega^k(M; \mathcal{E}) \to \Omega^k(M; \mathcal{E}) \) defined by
\[
\langle\langle \omega, \omega' \rangle\rangle_0(u) = \langle\langle A_k(u)\omega, \omega' \rangle\rangle_0(0)
\]
and consider the zeroth order pseudo-differential operator
\[
B_k(s + s'; u): H_{s + s'}(0)(\Lambda^k(M; \mathcal{E})) \to H_{s + s'}(0)(\Lambda^k(M; \mathcal{E}))
\]
defined by
\[
B_k(u) \equiv B_k(s + s', u) := (\text{Id} + \Delta_k(u))^{-1} \frac{d}{du}(A_k(u)(\text{Id} + \Delta_k(u)))^{s + s'}
\]
so that the following identity holds
\[
\frac{d}{du} \langle\langle \omega, \omega' \rangle\rangle_{s + s'}(u) = \langle\langle B_k(u)\omega, \omega' \rangle\rangle_{s + s'}(0).
\]
Let \( B_k(s + s', u) \) be the bounded operator in \( L^2(H_s(0)(\Lambda^k(M; \mathcal{E})) \oplus H_{s + s'}(0)(\Lambda^k(M; \mathcal{E}))) \) defined by
\[
B_k(u) = B_k(s + s', u) := \begin{pmatrix} 0 & 0 \\ 0 & B_k(s + s', u) \end{pmatrix}.
\]
Then we have, in view of (3.6),
\[
\frac{d}{du} \langle\langle \omega_1, \omega_2 \rangle\rangle_{s + s'}(u) = \langle\langle B_k(u)\omega_1, \omega_2 \rangle\rangle_{s + s'}(0).
\]
Proceeding as in [BFKM, Appendix 3], one obtains (cf. [BFKM, A3.10]) in view of the fact that the complex \( \mathcal{C}_u \) is algebraically acyclic,
\[
(3.7) \quad \frac{d}{du} \log T(\mathcal{C}_u) = -Fp_{\bar{z}_01} \int_0^1 x^{s-1} \frac{1}{2} \sum_{q=0}^n (-1)^q \text{Tr}(B_q(u)e^{-x\tilde{\Delta}_q(u)})dx
\]
where \( \tilde{\Delta}_q(u) \) denotes the \( q \)-Laplacian of \( \mathcal{C}_u \) with respect to the inner product (3.6).

By formula (1.23),
\[
\tilde{\Delta}_q(u) = \begin{pmatrix} \Delta_{q-1}(0) + \psi_{q-1}(u) & \eta_q(u) \\ \eta_q(u)^* & \Delta_q(u) + \psi_q(u) \end{pmatrix}
\]
where \( \begin{pmatrix} \psi_{q-1}(u) & \eta_q(u) \\ \eta_q(u)^* & \psi_q(u) \end{pmatrix} \) is a nonnegative selfadjoint operator of trace class \( (s, s' \text{ sufficiently large}) \).
By the remark after Proposition 1.5 we conclude, in view of definitions (1.5) and (1.7),

\[ -(\frac{1}{2} F p_z = 0 \frac{1}{\Gamma(z)} \int_0^1 x^{z-1} \sum_{q=0}^n (-1)^q \text{Tr}(B_q(u)e^{-x\Delta_q(u)})dx) \]

\[ = -\frac{1}{2} F p_z = 0 \frac{1}{\Gamma(z)} \int_0^1 x^{z-1} \sum_{q=0}^n (-1)^q \text{Tr}(B_q(u)e^{-x\Delta_q(u)}(\text{Id} - P_{q,u}))dx \]

\[ + \frac{1}{2} \sum_{q=0}^n (-1)^q \text{Tr}(B_q(u)P_{q,u}) \]

\[ = -\frac{1}{2} F p_z = 0 \frac{1}{\Gamma(z)} \int_0^1 x^{z-1} \sum_{q=0}^n (-1)^q \text{Tr}(B_q(u)e^{-x\Delta_q(u)})dx \]

where \( P_{q,u} = P_{q,u}(\{0\}) \) is the orthogonal projector onto the null space of \( \Delta_q(u) \).

Introduce

\[ a(x; u) := \sum_{q=0}^n (-1)^q \text{Tr}(B_q(s; u)e^{-x\Delta_q(s)}) \]

\[ = \sum_{q=0}^n (-1)^q \text{Tr}((\text{Id} + \Delta_q(u))^{-s}) A_q(u)^{-1} \frac{d}{du}(A_q(u)(\text{Id} + \Delta_q(u))^s)e^{-x\Delta_q(u)} \]

To investigate the right hand side of (3.8) introduce

\[ b(x; u) := \sum_{q=0}^n (-1)^q \text{Tr} (A_q(u)^{-1} (\frac{d}{du} A_q(u)) e^{-x\Delta_q(u)}) \]

According to [BZ],

\[ F p_z = 0 \frac{1}{\Gamma(z)} \int_0^1 x^{z-1} b(x; u)dx \]

is, in the case where \( \mu(u) = \mu \) is constant, given by

\[ \int_M \theta(\rho, \mu) \wedge \frac{d}{du} e_{CS}(M, g(0), g(u)) \]

and, when \( g(u) = g \) is constant by

\[ -1/2 \int_M V(\mu(0), \mu(u)) \wedge c(M, g) \]

Actually, in [BZ], these formulae are proven only for the case \( A = \mathbb{C} \), but the same arguments work ”word by word” for \( A \) arbitrary.
It remains to show that
\[ a(x; u) = b(x; u). \]
From the equality
\[ \frac{d}{du}((\text{Id} + \Delta_q(u))^s(\text{Id} + \Delta_q(u))^{-s}) = 0 \]
and the commutativity of the trace, $Tr AB = Tr BA$, we obtain
\[
Tr((\text{Id} + \Delta_q(u))^{-s}A_q(u)\frac{d}{du}(A_q(u)(\text{Id} + \Delta_q(u))^s)e^{-x\Delta_q(u)})
= Tr(A_q(u)^{-1}\frac{d}{du}A_q(u)e^{-x\Delta_q(u)})
+ Tr((\text{Id} + \Delta_q(u))^{-s}\frac{d}{ds}(\text{Id} + \Delta_q(u))^{-s})e^{-x\Delta_q(u)})
= Tr(A_q(u)^{-1}\frac{d}{du}A_q(u)e^{-x\Delta_q(u)})
+ s Tr((\text{Id} + \Delta_q(u))^{-1}\frac{d}{du}(\Delta_q(u))e^{-x\Delta_q(u)})
= Tr(A_q(u)^{-1}\frac{dA_q(u)}{du}e^{-x\Delta_q(u)}) + \frac{d}{du}Trf(\Delta_q(u))
\]
where $f(x, y) := -\int_y^\infty \frac{e^{-xr}}{1+r} dr$.
Since $\Delta_q(u)$ is selfadjoint and nonnegative one obtains, for $x > 0$,
\[
\|f(x, \Delta_q(u))\|_{tr} := \int_0^\infty \lambda |f(x, \lambda)| dN_{\Delta_q(u)}(\lambda) \leq \int_0^\infty \lambda e^{-\lambda x} dN_{\Delta_q(u)}(\lambda) < \infty.
\]
Therefore, $f(x, \Delta_q(u))$ is of trace class for $x > 0$ and
\[
\sum_{q=0}^{n} (-1)^q Tr f(x, \Delta_q(u)) = \sum_{q=0}^{n} (-1)^q Tr f(x, \Delta_q^+(u)) + \sum_{q=0}^{n} (-1)^q Tr f(x, \Delta_q^-(u))
= \sum_{q=1}^{n} (-1)^q (Tr f(x, \Delta_q^+(u)) - Tr f(x, \Delta_{q-1}^-))
= 0
\]
where we used that $\Delta_q^+(u)$ and $\Delta_q^-(u)$ are isospectral and, therefore,
\[ Tr f(x, \Delta_q^+(u)) = Tr f(x, \Delta_q^-(u)). \]
Thus, for any \( x \geq 0 \),

\[
a(x, u) = b(x, u) + \frac{d}{du} \sum_{q=0}^{n} (-1)^q Trf(x, \Delta_q(u)) = b(x; u).
\]

Combining this with (3.8)-(3.11), statement (i) in Proposition 3.1 and Proposition 3.2 follows.

In the remainder of this section we investigate how the relative torsion depends on the triangulation.

Suppose \( \tau_1 = (h_1, g_1) \) and \( \tau_2 = (h_2, g_2) \) are two generalized triangulation which admit a common subdivision \( \tau_0 = (h_0, g_0) \). Recall from [BFKM, Subsection 6.3] that \( \tau_0 \) is called a subdivision of \( \tau_1 \) if :

(i) \( Cr_q(h_1) \subseteq Cr_q(h_0) \), \( (0 \leq q \leq n) \), \( W_x^-(\tau_0) \subseteq W_x^-(\tau_1) \), \( (x \in Cr(h_1) \)

and

(ii) \( W_y^-(\tau_1) = \bigcup_{x \in Cr(h_1), x \in W_y^- (\tau_1)} \bigcup_{x \in Cr(h_1), x \in W_y^- (\tau_1)} \),

where \( Cr_q(h_\ldots) \) denotes the set of critical points of index \( q \), of \( h_\ldots \), \( W_x^-(\tau_1) \)

denotes the unstable manifold of \( x \in Cr(h_1) \) with respect to the gradient flow

\(-\text{grad}_g, h_1) \) and \( g_0 = g_1, h_0 = h_1 \) in a neighborhood of the critical points of \( h_1 \).

Given \( x \in Cr(h_0) \), there exist unique elements \( x_1 \in Cr(h_1) \), \( x_2 \in Cr(h_2) \) so

that \( x \in W_{x_j}^- (\tau_j) \) \( (j = 1, 2) \).

Introduce the function \( w = w_{\tau_0} = w(\tau_1, \tau_2; \tau_0); Cr(h_0) \to \mathbb{R} \) by setting

\[
\tag{3.13}
w(x) := \log \text{vol}(T_{x, x_2}^{\tau_2} \circ (T_{x, x_1}^{\tau_1})^{-1}
\]

where \( T_{x, x_j}^{\tau_j}; E_x \to E_j \) \( (j = 1, 2) \) denotes the parallel transport along an arbitrary

curve in \( W_{x_j}^- (\tau_j) \) joining \( x \) and \( x_j \). Define \( \omega_{\tau_1, \tau_2} = \omega(\tau_1, \tau_2; \tau_0) \) by

\[
\tag{3.14}
\omega_{\tau_1, \tau_2} := \sum_{x \in Cr(h_0)} (-1)^{\text{index}(x)} w(x).
\]

Notice that \( \omega(\tau_1, \tau_2; \tau_0) \) is independent of the choice of \( \tau_0 \), i.e.,

\[
\tag{3.15}
\omega(\tau_1, \tau_2; \tau_0) = \omega(\tau_1, \tau_2; \tau_0)
\]

for any generalized triangulation \( \tau_0 = (h_0, g_0) \) which is a subdivision of \( \tau_0 \).

To see it, notice that for any \( y \in Cr(h_0) \), there exists a unique \( x \in Cr(h_0) \)

with \( y \in W_{x}^- (\tau_0) \). Use that \( T_{y, x_j}^{\tau_j} = T_{x, x_j}^{\tau_j} T_{y, x}^{\tau_0} \) \( (j = 1, 2) \) to conclude that

\[
w_{\tau_0}(y) = w_{\tau_0}(x) \sum_{y \in Cr(h_0) \cap W_{x}^- (\tau_0)} (-1)^{\text{index}(y)} w_{\tau_0}(y) = w_{\tau_0}(x) \sum_{y \in Cr(h_0) \cap W_{x}^- (\tau_0)} (-1)^{\text{index}(y)}.
\]

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As \( \tilde{\tau}_0 \) is a subdivision of \( \tau_0 \)

\[
\sum_{y \neq x, y \in Cr(h_0) \cap W_x^- (\tau_0)} (-1)^{\text{index}(y)} = 0
\]

we conclude that \( \omega(\tau_1, \tau_2; \tilde{\tau}_0) = \omega(\tau_1, \tau_2; \tau_0) \). Moreover, if \( \tau_1, \tau_2 \) and \( \tau_3 \) are three generalized triangulation which admit a common subdivision \( \tau_0 \), then

\[
(3.16) \quad \omega_{\tau_1, \tau_2} + \omega_{\tau_2, \tau_3} = \omega_{\tau_1, \tau_3}.
\]

**Proposition 3.3** Assume that the generalized triangulations \( \tau_1 \) and \( \tau_2 \) admit a common subdivision \( \tau_0 \). Then

(i) \( \log R(\tau_2) - \log R(\tau_1) = -\omega_{\tau_1, \tau_2} \)

(ii) If \( \mu \) is parallel with respect to the canonical flat connection of \( E \), then \( R(\tau_1) = R(\tau_2) \) provided \( \tau_1 \) and \( \tau_2 \) have a common subdivision.

**Proof:** Statement (ii) follows from (i) by noticing that \( w(x) = 0, \forall x \in Cr(h_0) \) and thus \( \omega_{\tau_1, \tau_2} = 0 \).

To prove (i), notice that

\[
\log R(\tau_2) - \log R(\tau_1) = (\log R(\tau_2) - \log R(\tau_0)) + (\log R(\tau_0) - \log R(\tau_1)).
\]

In view of (3.16), it suffices to consider the case where \( \tau_2 = \tau_0 \). The subdivision \( \tau_2 \) can be obtained to be a sequence \( \tau_1 = \sigma_1, \ldots, \sigma_N = \tau_2 \) where \( \sigma_{j+1} = (h_{j+1}, g'_{j+1}) \) is a subdivision of \( \sigma_j = (h_j, g'_j) \) with \( Cr(h_{j+1}) = Cr(h_j) \cup \{x_{j+1}, y_{j+1}\} \) so that there exists \( z_j \in Cr(h_j) \) with \( x_{j+1}, y_{j+1} \in W^+_0 \) and \( \text{index}(x_{j+1}) = \text{index}(y_{j+1}) + 1 \). Recall that \( W^-_x \) denotes the unstable manifold associated to \( x \) and the gradient flow \( -\text{grad}_{g_j} h_j \). In view of (3.15), it suffices to consider the case where \( \tau_2 = \delta_2 \). To ease notation, we write \( \tau := \tau_1 = (h_1 g'_1), \sigma := \tau_2 = (h_2, g'_2), z := z_1, x := x_2, y := y_2 \). Then, with \( q_0 = \text{index}(z) \)

\[
Cr_q(h_2) = \begin{cases} 
Cr_q(h_1) & q \neq q', q' - 1 \\
Cr_q(h_1) \cup \{y'\} & q = q' - 1 \\
Cr_q(h_1) \cup \{x'\} & q = q'
\end{cases}
\]

Consider the following commutative diagram

\[
\begin{array}{ccc}
\text{Int}_s(\tau) & \xrightarrow{H_s(\Lambda(M, E))} & \mathcal{C}(\tau) \\
\text{Int}_s(\sigma) & \uparrow \mathcal{A} & \\
& \mathcal{C}(\sigma)
\end{array}
\]
where $A_q$ ($0 \leq q \leq n$) is defined as follows: for a section $s \in \Gamma(\mathcal{E}|_{Cr_q(h_2)})$ and a critical point $x \in Cr_q(h_1)$, set

$$A_q(s)(x) := \sum_{y \in (Cr_q(h_2) \cap W_x)} T_{yx}(s(y)).$$

where $T_{yx} : \mathcal{E}_y \to \mathcal{E}_x$ denotes the parallel transport from $y$ to $x$ along a curve in $W_x = W_x(\tau)$. The map $A$ is a morphism of cochain complexes of $\mathcal{A}$-Hilbert modules of finite type which induces an isomorphism in algebraic cohomology. As $\text{Int}_x$ and $A$ are of trace class, we then conclude from Proposition 1.15 that

$$\log \mathcal{R}(\tau) = \log \mathcal{R}(\sigma) + \log T(\mathcal{C}(A)).$$

Thus the claimed result follows once we show that

$$(3.17) \quad \log T(\mathcal{C}(A)) = \omega_{\sigma\tau}.$$

Formula (3.17) can be verified, using a localization argument: Notice that if $\mu$ is parallel, (3.17) holds as $\omega_{\sigma\tau} = 0$ and, using that $\log \mathcal{R}(\tau) = \log \mathcal{R}(\sigma) = 0$ by Theorem 0.1, $\log T(\mathcal{C}(A)) = \log \mathcal{R}(\tau) - \log \mathcal{R}(\sigma) = 0$. Further, if $\mathcal{E}$ admits a Hermitian structure $\mu_0$ which is parallel, then (3.11) remains valid. Indeed, consider the following commutative diagram

$$\begin{array}{ccc}
\mathcal{C}(\sigma, \mu) & \xrightarrow{A} & \mathcal{C}(\tau, \mu) \\
\downarrow \text{Id}_{\sigma, \mu, \mu_0} & & \downarrow \text{Id}_{\tau, \mu, \mu_0} \\
\mathcal{C}(\sigma, \mu_0) & \xrightarrow{A} & \mathcal{C}(\tau, \mu_0)
\end{array}$$

Then, according to Proposition 1.12,

$$\log T(\mathcal{C}(\text{Id}_{\sigma, \mu, \mu_0})) + \log T(\mathcal{C}(A, \mu_0)) = \log T(\mathcal{C}(A, \mu)) + \log T(\mathcal{C}(\text{Id}_{\tau, \mu, \mu_0})).$$

By Proposition 1.14, $(j = 1, 2)$

$$\log T(\mathcal{C}(\text{Id}_{\sigma, \mu, \mu_0})) - \log T(\mathcal{C}(\text{Id}_{\tau, \mu, \mu_0})) = \sum_q (-1)^q \log \text{vol}(\text{Id}_{q, \sigma, \mu, \mu_0}) - \sum_q (-1)^q \log \text{vol}(\text{Id}_{q, \tau, \mu, \mu_0}) = \sum_{y \in Cr(h_2)} (-1)^{\text{index}(y)} \log \text{vol}(\text{Id}_{y, \mu, \mu_0}) - \sum_{y \in Cr(h_1)} (-1)^{\text{index}(y)} \log \text{vol}(\text{Id}_{y, \mu, \mu_0})$$

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\[
= (-1)^{\text{index}(x')} \log \text{vol} (\text{Id}_{x', \mu, \mu_0}) \\
+ (-1)^{\text{index}(y')} \log \text{vol} (\text{Id}_{y', \mu, \mu_0}).
\]

Combining the above equalities with \( \log T(C(A, \mu_0)) = 0 \) we obtain
\[
\log T(C(A, \mu)) = (-1)^{\text{index}(x')} \log \text{vol} (\text{Id}_{x', \mu, \mu_0}) + \\
+ (-1)^{\text{index}(y')} \log \text{vol} (\text{Id}_{y', \mu, \mu_0}).
\]

Observe that
\[
\log \text{vol} (\text{Id}_{x', \mu, \mu_0}) = \log \text{vol}_{\mu} (T_{x', z'}) + \log \text{vol} (\text{Id}_{z', \mu, \mu_0})
\]
and, similarly,
\[
\log \text{vol} (\text{Id}_{y', \mu, \mu_0}) = \log \text{vol}_{\mu} (T_{y', x_0}) + \log \text{vol} (\text{Id}_{z', \mu, \mu_0}).
\]

As \( \text{index}(x') = \text{index}(y') + 1 \), this leads to
\[
\log T(C(A, \mu)) = (-1)^{\text{index}(x')} \log \text{vol}_{\mu} (T_{x', z'}) \\
+ (-1)^{\text{index}(y')} \log \text{vol}_{\mu} (T_{y', z'}) \\
= \omega_{zT}
\]
which establishes (3.17) in the case where \( \mathcal{E} \) admits a Hermitian structure which is parallel.

Now use a standard localization to conclude that (3.17) is true in general.

\section*{4 Proof of Theorem 0.1}

\subsection*{4.1 Outline of the Proof of Theorem 0.1}

We first prove Theorem 0.1 in the case the Riemannian metric \( g \) is the same as the metric \( g' \) of the generalized triangulation \( \tau = (h, g') \) and the Hermitian structure \( \mu \) is \( \tau \)-admissible, i.e. there exists a neighborhood \( U_h \) of the critical points of \( h \) so that on \( U_h \), \( \mu \) is parallel with respect to the canonical flat connection on \( \mathcal{E} \rightarrow M \).

From Theorem 2.9 we know that
\( (A) \log R(t) = \log \mathcal{R} + \int_0^t \frac{dt}{d \mathcal{R}} \log \mathcal{R}(t) dt \) is an affine function of \( t \),

hence \( \mathcal{R}(t) \) has an asymptotic expansion with \( \log \mathcal{R} \) as the free term.

Recall from the proof of Proposition 2.1 (iii) that, for \( t \) sufficiently large, \((H_0(\Lambda(M; \mathcal{E})), d(t))\) is the direct sum of two subcomplexes,
\[(H_0(\Lambda(M;\mathcal{E})),d(t)) = (\Omega_{sm}(t),d(t)) \oplus (H_{0,la}(t),d(t))\]

where

\[H_{k,0} := H_0(\Lambda^k(M;\mathcal{E})),\]
\[\Omega_{k}^{sm}(t) = Q_k(t)(H_{k,0}),\]
\[H_{k,0,la}(t) = (Id-Q_k(t))(H_{k,0})\]
\[Q_k(t) \text{ denotes the orthogonal spectral projector } Q_k(t) : H_{k,0} \rightarrow H_{k,0} \text{ of the } k\text{-Laplacian } \Delta_k(t) \text{ corresponding to the interval } [0,1].\]

Notice that \(\Omega_{k}^{sm}(t)\) consists of smooth forms and that \((H_{0,la}(t),d(t))\) is an algebraically acyclic \(\zeta\)-regular complex of \(s\)F type. Notice also that \((\Omega_{sm}(t),d(t))\) is a \(\zeta\)-regular complex of finite type for \(t\) large enough. The finite type property follows from [BFKM] Theorem 5.5. Denote by \(g_{s,sm}(t)\) the restriction of \(g_s(t)\) to \(\Omega_{sm}(t)\). This is a morphism of trace class for \(s > \frac{d}{2} + 1\) since \(g_s(t)\) is of trace class by Proposition 2.5. We have the following short exact sequence of algebraically acyclic, \(\zeta\)-regular complexes of \(s\)F type,

\[(4.1) \quad 0 \rightarrow \mathcal{C}(g_{s,sm}(t)) \overset{I}{\rightarrow} \mathcal{C}(g_s(t)) \overset{P}{\rightarrow} H_{0,la}(t) \rightarrow 0\]

where \(I\), resp. \(P\), is the obvious inclusion, resp. projection. One verifies in a straightforward way that (4.1) satisfies the assumptions in Lemma 1.14 and therefore, with

\[(4.2) \quad \mathcal{R}_{sm}(t) := T(\mathcal{C}(g_{s,sm}(t))),\]

we obtain the decomposition

\[(B) \quad \log \mathcal{R}(t) = \log \mathcal{R}_{sm}(t) + \log T(H_{0,la}(t)).\]

For consistency with the notation in [BFKM] we write

\[\log T_{la}(t) := \log T(H_{0,la}(t)).\]

The two terms, \(\log \mathcal{R}_{sm}(t)\) and \(\log T_{la}(t)\), will each be treated separately. To obtain an asymptotic expansion of \(\log \mathcal{R}_{sm}(t)\) as \(t \rightarrow \infty\), we proceed in two steps. Recall that \(f(t)\) is given by the composition

\[f(t) : (\Omega_{sm}(t),d(t)) \overset{\epsilon^t}{\rightarrow} (\Omega,d) \overset{Int}{\rightarrow} (\mathcal{C},\delta).\]

We show in subsection 4.2, Proposition 2.1 (i) that

\[\mathcal{R}_{sm}(t) = T(\mathcal{C}(f(t))).\]

The morphism \(f(t)\), unlike \(g_{s,sm}(t)\), can be studied using the Witten-Helffer-Sjöstrand theory (cf [BFKM, section 5]). We show in subsection 4.2, Proposition
4.1 (ii) that log T(C(f(t))) has an asymptotic expansion which we calculate up to terms of order $0(\frac{1}{t})$. Proposition 4.1 implies that:

(C) log $R_{sm}(t)$ admits an asymptotic expansion for $t \to \infty$ of the form

$$\log R_{sm}(t) = \dim E_x \left( \sum_j (-1)^j j m_j \right) t - \left( \sum_j (-1)^j \left( \frac{n}{4} - \frac{1}{2} \right) m_j \dim E_x \right) \log \left( \frac{1}{t} \right) + 0(\frac{1}{t}).$$

Concerning log $T_{la}(t)$ In section 4.2 we will establish:

(D) (i) log $T_{la}(t)$ admits an asymptotic expansion as $t \to \infty$ and

$$FT_{t=\infty}(\log T_{la}(t)) = -FT_{t=\infty}(\log R_{sm}(t)) + \int_M a$$

where $a$ is a local density on $M$ which vanishes in a neighborhood of the critical points of $h$.

(ii) If $\mu$ is parallel with respect to the canonical flat connection, $\int_M a = 0$.

The results (A)-(D) prove Theorem 0.1 in the case where $g = g'$ and $\mu$ is $\tau$-admissible. Theorem 0.1, in full generality, follows when (A)-(D) are combined with (E) below: Let $g_1$ and $g_2$ be two Riemannian metrics of $M$ and $\mu_1, \mu_2$ two Hermitian structures for $E \to M$. Denote the corresponding relative torsions by $R(g_1, \mu_1)$ and $R(g_2, \mu_2)$. Propositions 3.1 and 3.2 imply that:

(E) (i) $\log R(g_1, \mu_1) - \log R(g_2, \mu_2) = \int_M a_{g_1, g_2, \mu_1, \mu_2}$

where $a_{g_1, g_2, \mu_1, \mu_2}$ is a local density on $M$.

(ii) If $\mu$ is parallel with respect to the canonical flat connection, or $\dim M$ is odd, then $a_{g_1, g_2, \mu_1, \mu_2} = 0$.

4.2 Asymptotic expansion of log $R_{sm}(t)$

In this subsection we prove the statement (C) in subsection 4.1. By the Witten-Helffer-Sjöstrand theory, $f(t) := \text{Int} \cdot e^{th}$ is an isomorphism of cochain complexes for $t$ sufficiently large. Therefore the mapping cone $C(f(t))$ is an algebraically acyclic, $\zeta$-regular complex of $sF$ type and thus admits a torsion, $T(C(f(t)))$.

**Proposition 4.1** For $t$ sufficiently large,

(i) $\log R_{sm}(t) = \log T(C(f(t)))$;
(ii) \( \log T(\mathcal{C}(f(t))) \) admits an asymptotic expansion for \( t \to \infty \) of the form

\[
\log T(\mathcal{C}(f(t))) = \dim E_x \left( \sum_j (-1)^j jm_j \right) t - \left( \sum_j (-1)^j \left( \frac{n}{2} - \frac{1}{2} \right) m_j \dim E_x \right) \log(\frac{2}{t}) + 0(\frac{1}{t})
\]

where \( m_q \) denotes the number of critical points of index \( q \) of the Morse function \( h \).

**Proof** (i) Notice that the morphism \( f(t) \) is equal to the composition \((s > n+2)\)

\[
(\Omega_{sm}(t), d(t)) \xrightarrow{e^{th}} H_s(\Lambda(M; E)) \xrightarrow{Int_s} \mathcal{C}(M, \tau, F)
\]

whereas \( g_{s, sm}(t) \) is given by

\[
(\Omega_{sm}(t), d(t)) \xrightarrow{e^{th}} (H_0(\Lambda(M; E)), d) \xrightarrow{(\Delta + Id)^{-s/2}} (H_s(\Lambda(M; E)), d)
\]

\[
\xrightarrow{Int_s} \mathcal{C}(M, \tau, F).
\]

By Proposition 2.5, \( Int_s \) is a morphism of trace class, multiplication by \( e^{th} \) is a morphism of trace class as \( \Omega_{sm}(t) \) is a cochain complex of finite rank (cf Examples 1.6) and \((\Delta + Id)^{-s/2}\) is an isometry. Each of them induces an isomorphism in algebraic cohomology (cf Proposition 2.1). Therefore we can apply Proposition 1.15 to (4.3) and (4.4) to obtain

\[
\log T(\mathcal{C}(f(t))) = \log T(\mathcal{C}(e^{th})) + \log T(\mathcal{C}(Int_s))
\]

and

\[
\log T(\mathcal{C}(g_{s, sm}(t))) = \log T(\mathcal{C}(e^{th})) + \log T(\mathcal{C}(Int_s(\Delta + Id)^{-s/2})).
\]

In view of Proposition 1.16 and the fact that \((\Delta + Id)^{-s/2}\) is an isometry we conclude that

\[
\log T(\mathcal{C}(Int_s)) = \log T(\mathcal{C}(Int_s(\Delta + Id)^{-s/2})).
\]

Further, \( e^{th} = In_{s,0} e^{th}_s \) is a morphism

\[
(\Omega_{sm}(t), d(t)) \xrightarrow{e^{th}} H_s(\Lambda(M; E)) \xrightarrow{In_{s,0}} H_0(\Lambda(M; E))
\]

with \( In_{s,0} \) and \( e^{th}_s \) being both morphisms of trace class and inducing isomorphisms in algebraic cohomology (cf Proposition 2.1). Thus, applying Proposition 1.15 once more, we obtain, in view of Proposition 2.3,

\[
\log T(\mathcal{C}(e^{th})) = \log T(\mathcal{C}(e^{th}_s)).
\]

Combining (4.5) - (4.8) leads to the proof of statement (i).
(ii) Recall from [BFKM, section 5.2] the following commutative diagram (for \( t \) sufficiently large)

\[
\begin{array}{ccc}
(\Omega_{sm}(t), \alpha(t)d(t)) & \xrightarrow{S(t)} & (\Omega_{sm}(t), d(t)) \\
\Phi + 0\left(\frac{1}{t}\right) \searrow & & \downarrow f(t) \\
(C, \delta)
\end{array}
\]

(4.9)

where \( \Phi \) is a morphism which is an isometry, \( S(t) \) is scaling morphism given by \( S_k(t) := e^{-tk}\left(\frac{\pi t}{4}\right)^{k/2} \), and \( \alpha = \alpha(t) \) is chosen so that the diagram above is commutative, \( \alpha(t) = e^t(\frac{\pi}{4})^{1/2} \).

For \( t \) sufficiently large, \( S(t), f(t), \Phi + 0\left(\frac{1}{t}\right) \) are isomorphisms of cochain complexes. Thus, by Lemma 1.11, the mapping cones \( C(\Phi + 0\left(\frac{1}{t}\right)), C(S(t)) \) and \( C(f(t)) \) are algebraically acyclic. By Proposition 1.15,

\[
\log T(C(\Phi + 0\left(\frac{1}{t}\right))) = \log T(C(S(t))) + \log T(C(f(t))).
\]

Using Proposition 1.12, one verifies that \( \log T(C(Id + 0\left(\frac{1}{t}\right))) = 0\left(\frac{1}{t}\right) \).

Therefore

\[
\log T(C(f(t))) = -\log T(C(S(t))) + 0\left(\frac{1}{t}\right).
\]

By Proposition 1.12,

\[
\log T(C(S(t))) = \sum (-1)^j (\log S_j(t)) \dim \Omega_{sm}(t)_j = \sum (-1)^j \log(e^{-tj}\left(\frac{\pi}{4}\right)^{k/2}) \dim \Omega_{sm}(t)_j
\]

Notice that \( \dim \Omega_{sm}(t)_j = m_j \dim \mathcal{E}_x \) where \( m_j \) is the number of critical points of \( h \) of index \( j \). In view of (4.10) we obtain

\[
\log C(f(t)) = (\sum (-1)^j jm_j \dim \mathcal{E}_x)t
\]

\[-(\sum (-1)^j (\frac{\pi}{4} - \frac{j}{2})m_j \dim \mathcal{E}_x) \log \frac{\pi}{4} + 0\left(\frac{1}{t}\right). \]

4.3 Asymptotic expansion of \( \log T_{\alpha}(t) \)

In this section we prove the statement (D) in subsection 4.1. As \( \log T_{\alpha}(t) = \log R(t) - \log R(t) \) and in view of Theorem 2.9 and Proposition 4.1 \( \log T_{\alpha}(t) \) admits an asymptotic expansion for \( t \to \infty \).
The arguments to prove (D) follow closely the ones in [BFKM, section 6.2]: we will derive statement (D) from a relative version of this statement, Theorem 4.2, and from the validity of (D) in some simple cases.

We consider systems \( \mathcal{F} := (M^n, \mathcal{E}, \nabla, \mu, g, \tau) \), where \((\mathcal{E}, \nabla)\) is a bundle of \( \mathcal{A} \)-Hilbert modules equipped with a flat connection, \( \mu \) a hermitian structure, \( g \) a Riemannian metric and \( \tau = (h, g') = g \) a generalized triangulation with the metric as \( g' = g \) and we suppose that \( \mu \) is admissible with respect to \( \tau \), i.e., there exists an open neighborhood \( U_h \) of the critical points so that on \( U_h \), \( \mu \) is parallel with respect to the connection \( \nabla \). Introduce \( V_F(t, \epsilon) := \frac{1}{2} \sum_q (-1)^{q+1} q \log(\Delta_q(t) + \epsilon) \).

**Proposition 4.2** For any \( \epsilon > 0 \) there exists a smooth density \( \alpha_\mathcal{F}(\epsilon) \) on \( M \setminus Cr(h) \), which is polynomial in \( \epsilon \) and a local quantity in the sense of [BFKM] section 2 so that the following statement hold:

(i) If \( \mathcal{F}' := (M^n, \mathcal{E}, \nabla, \mu, g, \tau_D) \) denotes the system obtained from \( \mathcal{F} \) by replacing the triangulation \( \tau = (h, g) \) by its dual \( \tau_D = (n-h, g) \), then

\[ \alpha_\mathcal{F}(\epsilon) + (-1)^{n+1} \alpha_\mathcal{F}'(\epsilon) = 0. \]

(ii) If \( \mathcal{F} \) and \( \tilde{\mathcal{F}} \) are two systems as above and \( \mathcal{F} \otimes \tilde{\mathcal{F}} \) denotes the system defined by

\[ \mathcal{F} \otimes \tilde{\mathcal{F}} := (M \times \hat{M}, \mathcal{E} \otimes \tilde{\mathcal{E}}, \mu \otimes \tilde{\mu}, g \times \hat{g}, \tau \times \hat{\tau}), \]

with \( \hat{\nabla} = \nabla \otimes id + id \otimes \hat{\nabla} \), then

\[ (4.12) \quad \alpha_{\mathcal{F} \otimes \tilde{\mathcal{F}}}(\epsilon) = (\alpha_{\mathcal{F}}(\epsilon) \otimes e(\hat{M}, \hat{g}) + e(M, g) \otimes \tilde{\alpha}_{\mathcal{F}}(\epsilon)) \dim W, \]

where \( e(M, g) \) denotes the Euler form of \( (M, g) \).

(iii) The density \( \alpha_{\mathcal{F}}(\epsilon) \) vanishes on \( U_h - Cr(h) \).

(iv) Assume \( \mathcal{F} \) and \( \tilde{\mathcal{F}} \) are two systems as above so that \( \mathcal{F}Cr_q(h) = \tilde{\mathcal{F}}Cr_q(\hat{h}) \) \((0 \leq q \leq n)\), and the bundles \( \mathcal{E} \) and \( \tilde{\mathcal{E}} \) have isomorphic \( \mathcal{A} \)-Hilbert modules as fibers. Then \( V_F(t, \epsilon) - V_{\tilde{F}}(t, \epsilon) \) has an asymptotic expansion with

(a) \( FT_t(\mathcal{F}(t, \epsilon) - \tilde{V}_{\tilde{F}}(t, \epsilon)) = \int_{M \setminus Cr(h)} \alpha_{\mathcal{F}}(\epsilon) - \int_{\hat{M} \setminus Cr(\hat{h})} \alpha_{\tilde{F}}(\epsilon) \)

(b) \( FT_t(\log T_{1a}(t)) - FT_t(\log \tilde{T}_{1a}(t)) = \int_{M \setminus Cr(h)} \alpha_{\mathcal{F}}(0) - \int_{\hat{M} \setminus Cr(\hat{h})} \alpha_{\tilde{F}}(0) \)

**Proof:** We begin with the construction of the density \( \alpha_{\mathcal{F}}(\epsilon) \). Away from the critical points of \( h \) we choose a coordinate system for \( \mathcal{E} \to M \). In these coordinates we calculate inductively the quantities \( r_{2-j}(h, \epsilon; x, \xi, t, \mu) \), by the formulae 6.59 in [BFKM], from the symbol of the operator with parameter \( \Delta_q(t) + \epsilon, \)
which is elliptic with parameter \((t)\) away from \(Cr(h)\) cf [BFKM] (3.2). We are interested in the quantity \(r_{q-2-n}^2\) only. We use formula (3.4) in [BFKM] to obtain from \(r_{q-2-n}^2\) the density \(\alpha_{q}(h,\epsilon)\) on \(M \setminus Cr(h)\). We define

\[(4.13) \quad \alpha_{q}(h,\epsilon) := 1/2 \sum_{q} (-1)^{q+1} q \alpha_{q}(h,\epsilon).\]

Since by construction \(r_{q-2-n}^2\) is a polynomial in \(\epsilon\) of degree smaller that \(n\) so is \(\alpha_{q}(h,\epsilon)\).  

(i) follows from the following homogeneity property (cf [BFKM] (6.60)):

\[r_{-2-n}(h, x, -t, \xi, \mu) = (-1)^n r_{-2-n}(h, x, \xi, t, \mu).\]

and by a straightforward verification

\[r_{-2-n}(n - h, x, \xi, t, \mu) = r_{-2-n}(h, x, \xi, -t, \mu).\]

To prove (ii) we consider systems \(G = (M, E, \nabla, \mu, g, \omega)\), where \(M, E, \nabla, \mu, g\) are as above and \(\omega\) is a closed 1-form on \(M\). A system \(F = (M^n, E, \nabla, \mu, g, \tau = (g, h))\) gives rise to a system \(G\) by taking \(\omega = dh\). For any such \(G\), define the Witten deformation by taking \(\omega\) instead of \(dh\) and then the Witten Laplacians \(\Delta_{q}(t)\) for any real number \(t\). If the 1-form \(\omega\) has no zeros, \(\Delta_{q}(t)\) is elliptic with parameter \((t)\) away from \(Cr(h)\) cf [BFKM] (3.2). We are interested in the quantity \(r_{q-2-n}^2\) only. We use formula (3.4) in [BFKM] to obtain from \(r_{q-2-n}^2\) the density \(\alpha_{q}(h,\epsilon)\) on \(M \setminus Cr(h)\). We define

\[(4.13) \quad \alpha_{q}(h,\epsilon) := 1/2 \sum_{q} (-1)^{q+1} q \alpha_{q}(h,\epsilon).\]

Since by construction \(r_{q-2-n}^2\) is a polynomial in \(\epsilon\) of degree smaller that \(n\) so is \(\alpha_{q}(h,\epsilon)\).  

(i) follows from the following homogeneity property (cf [BFKM] (6.60)):

\[r_{-2-n}(h, x, -\xi, -t, \mu) = (-1)^n r_{-2-n}(h, x, \xi, t, \mu).\]

and by a straightforward verification

\[r_{-2-n}(n - h, x, \xi, t, \mu) = r_{-2-n}(h, x, \xi, -t, \mu).\]

To prove (ii) we consider systems \(G = (M, E, \nabla, \mu, g, \omega)\), where \(M, E, \nabla, \mu, g\) are as above and \(\omega\) is a closed 1-form on \(M\). A system \(F = (M^n, E, \nabla, \mu, g, \tau = (g, h))\) gives rise to a system \(G\) by taking \(\omega = dh\). For any such \(G\), define the Witten deformation by taking \(\omega\) instead of \(dh\) and then the Witten Laplacians \(\Delta_{q}(t)\) for any real number \(t\). If the 1-form \(\omega\) has no zeros, \(\Delta_{q}(t)\) is elliptic with parameter and the general theory in [BFKM], section2 implies that for any fixed \(\epsilon > 0\), \(V_{G}(t,\epsilon) := 1/2 \sum_{q} (-1)^{q+1} q \log(\Delta_{q}(t) + \epsilon)\) has an asymptotic expansion for \(t \to \infty\), whose free term is \(\int_{M} \alpha_{q}\), with \(\alpha_{q}\) a local density on \(M\). Following [BMFK] section 2 this density is calculated in the same way as the density \(\alpha_{q}\) (using \(\omega\) instead of \(dh\)).

Since \(\mathcal{F}|_{M \setminus Cr(h)}\) is locally isomorphic to the restriction to an open set of a system \(G = (M, E, \nabla, \mu, g, \omega)\) such that \(M\) is closed and \(\omega\) has no zeros, it suffices to check (4.11) for \(\alpha_{q}\) instead of \(\alpha_{q}\) and \(\alpha_{q}\).

For a system \(G\) and \(u > 0, t > 0\) consider the operator \(e^{-u \Delta_{q}(t)}\) which is a smoothing operator and denote by \(\lambda_{q}(u, t)\) the pointwise (von Newman)trace of the restriction of its Schwartz kernel to the diagonal. This provides a two parameter family (in \(u\) and \(t\)) of densities on \(M\). Denote by

\[\lambda(u, t) := 1/2 \sum_{q} (-1)^{q+1} q \lambda_{q}(u, t).\]

Define the smooth three parameter family, \(\eta(s, t, \epsilon)\), of densities on \(M\) for real of \(s\) sufficiently large,

\[(4.14) \quad \eta(s, t, \epsilon) = \frac{1}{\Gamma(s)} \int_{0}^{\infty} u^{s-1} e^{-u \epsilon} \lambda_{q}(u, t) du.\]

which by analytic continuation is holomorphic in \(s\) near \(0 \in \mathbb{C}\). Denote by \(\theta_{q}(t, \epsilon)\) the densities valued function in \(t\) and \(\epsilon\),

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\[ \theta(t, \epsilon) := \frac{d}{ds}_{s=0} \eta(s, t, \epsilon). \]

For the system \( \mathcal{G} \otimes \tilde{\mathcal{G}} \), we can prove that:

\[ (4.15) \quad \theta_{\mathcal{G} \otimes \tilde{\mathcal{G}}}(t, \epsilon) = \theta_{\mathcal{G}}(t, \epsilon) \otimes e(\tilde{M}, \tilde{g}) \dim W + e(M, g) \otimes \theta_{\tilde{\mathcal{G}}}(t, \epsilon) \dim \mathcal{W}. \]

This can be derived as in the proof of Proposition 2.4 in [BFKM] from the following facts:

(i): \( \Delta_{G \otimes \tilde{G}}(t) = \Delta_{G} \otimes \text{Id} + \text{Id} \otimes \Delta_{\tilde{G}}(t) \), whose proof is similar to the proof of Proposition 2.4 in [BFKM] and for ant \( t \),

(ii): \( \eta(0, t, \epsilon = 0) = e(M, g) \dim W \), whose proof follows from the local index theorem of Bismut and Zhang. This takes care of (4.11).

For (iii), we use the locality of the density \( \alpha_{F}(\epsilon) \) and the explicit formula of \( \Delta_{q}(t) \). In admissible coordinates in the neighborhood of the critical points \( \Delta_{q}(t) \), is the same as \( \Delta_{q}(t) \), for a product of systems \( \mathcal{G} \) with underlying manifolds of dimension one. Using (4.11) and the vanishing of the Euler form on \( M = R \), the result follows.

(iv) a) is actually Proposition 6.6 in [BFKM] and (b) follows from Lemma 6.7 of [BFKM].

**Proof of statement (D):** We want to apply Proposition 4.2. Set \( \tilde{M} := M \), \( \tilde{\tau} := \tau \), \( g = \tilde{g}, \tilde{\rho} \) the trivial representation of \( \Gamma \equiv \pi_{1}(M) \) on \( W \). Then the associated bundle \( \tilde{E} \to M \) is trivial ; we choose \( \tilde{\mu} \) the trivial Hermitian structure. Then by (2.15) and the equality of analytic and Reidemeister torsion for the trivial representation we have \( \tilde{R} = 1 \). Since \( \log \tilde{R}(t) \) admits an asymptotic expansion by (B) so does \( \log \tilde{T}_{ia}(t) \). Since the free term of the expansion of \( \log \tilde{R} \) is zero, one obtains

\[ (4.16) \quad FT_{t=\infty} \log \tilde{T}_{ia}(t) = \left( \sum_{j} (-1)^{j} \left( \frac{n}{2} - \frac{j}{2} \right) m_{j} \dim E_{x} \right) \log \pi. \]

Statement (i) in (D) follows then from Proposition 4.2 (iv) . To prove statement (ii), observe that since \( \mu \) is parallel with respect to the canonical flat connection \( \nabla \), the Hodge \( * \) operator induces an isometry between \( L_{2}(\Lambda^{k}(M; E)) \) and \( L_{2}(\Lambda^{n-k}(M; E)) \) operator and conjugates \( \Delta_{k}(t) \) with \( \Delta_{n-k}(-t) \). Thus \( \Delta_{k}(t) \) and \( \Delta_{n-k}(t) \) are isospectral and then by the definition of \( V_{\tau}(t, \epsilon) \) we have :

\[ V_{\tau}(t, \epsilon) = (-1)^{n+1} V_{\tilde{\tau}}(t, \epsilon) \]

and

\[ V_{\tilde{\tau}}(t, \epsilon) := (-1)^{n+1} V_{\tilde{\tau}}(t, \epsilon). \]

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Therefore
\[ V_F(t, \epsilon) - V_{\tilde{F}}(t, \epsilon) = (-1)^{n+1}V_F'(t, \epsilon) - (-1)^{n+1}V_{\tilde{F}'}(t, \epsilon), \]
and thus by Proposition 4.2 (iv) we have
\[ FT_\infty \log T_{la}(F, t) - FT_\infty \log T_{la}(\tilde{F}, t) = \]
\[ = (-1)^{n+1}FT_\infty \log T_{la}(F', t) - (-1)^{n+1}FT_\infty \log T_{la}(\tilde{F}', t), \]
Again by Proposition 4.2 (iv)
\[ \int_{M \setminus Cr(h)} \alpha_F(0) - \int_{M \setminus Cr(h)} \alpha_{\tilde{F}}(0) = \]
\[ = (-1)^{n+1}(\int_{M \setminus Cr(h)} \alpha_F'(0) - \int_{M \setminus Cr(h)} \alpha_{\tilde{F}'}(0)). \]
In view of (4.12), (D) (i) and
\[ \int_{M \setminus Cr(h)} \alpha_F = \int_{M \setminus Cr(h)} \alpha_{\tilde{F}} = 0 \]
because \(\mu\) is parallel one obtains
\[ \int_{M \setminus Cr(h)} \alpha_F = (-1)^{n+1}(\int_{M \setminus Cr(h)} \alpha_{F'}). \]
Statement (D)(ii) follows by combining this last formula with Proposition 4.2 (iv) \(\blacksquare\)

### 4.4 Proof of Proposition 0.1

Consider the system \(\mathcal{F} := (M^n, \rho, g, \mu, \tau) = (M^n, \mathcal{E}, \Delta, g, \mu, \tau), \tau = (h, g')\)
and denote by \(X\) the vector field \(X := -\text{grad}_g h\). \(X\) defines a smooth map \(X : M \setminus Cr(h) \rightarrow TM \setminus M\). Denote by
\[ \beta_x := \beta(M, \rho, \mu, g, \tau) = \theta(\rho, \mu) \wedge X^*(\Psi(TM, g)) \in \Omega^n(M \setminus Cr(h)). \]
Observe that if \(\mu\) is parallel in the neighborhood of \(Cr(h)\) both \(\alpha_x\), by Proposition 4.2 (iii), and \(\beta_x\) vanish in the neighborhood of \(Cr(h)\).

Proposition 4.2 (ii) and the equalities (3.1) and (3.2′′) imply that for
\[ \gamma(M, \rho, \mu, g, \tau) = \alpha(M, \rho, \mu, g, \tau) \] or \(\beta(M, \rho, \mu, g, \tau)\) we have
\[
\begin{align*}
&\gamma(M_1 \times M_2, \rho_1 \otimes \rho_2, g_1 \times g_2, \mu_1 \otimes \mu_2, \tau_1 \times \tau_2) = \\
&\gamma(M_1, \rho_1, g_1, \mu_1, \tau_1)\chi(M_2)\dim(W_2) + \chi(M_1)\dim(W_1)\gamma(M_2, \rho_2, g_2, \mu_2, \tau_2)
\end{align*}
\]
Choose a hermitian structure $\mu_0$ which is parallel in the neighborhood of $Cr(h)$. Introduce the quantity:

$$
S(M^n, \rho, \mu, \mu_0, g, \tau) = \log R(M^n, \rho, \mu_0) + 
+ \frac{1}{2} \int_{M \setminus Cr(h)} \beta(M^n, \rho, \mu_0) - \frac{1}{2} \int_M V(\rho, \mu, \mu_0) e(M, g)
$$

Proposition 0.1 will be derived from the following four statements:

(A) $S(M^n, \rho, \mu, \mu_0, g, \tau)$ is independent of $\mu, \mu_0, g, \tau$. Therefore write $S(M^n, \rho)$ instead of $S(M^n, \rho, \mu, \mu_0, g, \tau)$.

(B): If $\rho$ is unimodular then $S(M, \rho) + (-1)^{n+1} S(M, \rho) = 0$.

(C): $S(M, \rho) = (-1)^{n+1} S(M, \rho^\sharp)$.

(D): $S(M_1 \times M_2, \rho_1 \otimes \rho_2) = S(M_1, \rho_1) \chi(M_2) \operatorname{dim} W_1 + \chi(M_1) S(M_2, \rho_2) \operatorname{dim} W_2$.

(A) follows essentially from Propositions 3.1-3.3. The independence on $\mu_0$ follows from (3.1)', (3.1)" and (3.1)"', the independence on $\mu$ from Proposition 3.2 and (3.2)', the independence on $g$ from Proposition 3.2 and (3.2)" and the independence on $\tau$ can be checked out in the following way: One consider $\tau'$ a subdivision of $\tau$ so that only cells of $\tau$, lying in a contractible open set $U$ are subdivided. One choose $\mu = \mu_0$ parallel on $U$ in addition of being parallel in a neighborhood of the critical points of $h$. Since $\omega_{\tau, \tau'}$ is zero in this case, $S(M, \rho, ..\tau) = S(M, \rho, ..\tau')$.

To check (B) we choose $\mu = \mu_0$ and $\theta(\rho, \mu_0) = 0$. In view of the unimodularity this is possible. The result follows then from (3.2") and Proposition 4.2 (ii).

To check (C) one chooses again $\mu = \mu_0$. In view of (3.2") it suffices to check that

$$
\int_M \alpha(M, \rho, \mu, \rho^\sharp, g, \mu^\sharp, \tau, \epsilon) + (-1)^n \int_M \alpha(M, \rho^\sharp, g, \mu^\sharp, \tau, \epsilon) = 0.
$$

With the notation from Subsection 4.2 and in view of the fact that the $q$-Laplacian corresponding to $(\rho, \mu, g, h)$ is conjugated by the Hodge star operator to the $(n-q)$-Laplacian corresponding to $(\rho^\sharp, \mu^\sharp, g, n-h)$, the right hand side of the equality above is exactly

$$
(4.18) \quad \delta_{F}(h, \epsilon) := n/2 \sum_q (-1)^{q+1} \alpha_q F(h, \epsilon).
$$

We proceed now as in the proof of Proposition 4.2 (iv). Given the system $F$ one chooses the system $\tilde{F}$ with the same underlying Riemannian manifold $(M, g)$.
the same triangulation $\tau$ but with $\tilde{\rho}$ the trivial representation over the same $A$
Hilbert module and with $\tilde{\mu}$ a parallel hermitian structure.

Introduce $W_F(t, \epsilon) := \frac{1}{2} \sum_q (-1)^q \log(\Delta_q(t) + \epsilon)$. By the same arguments as in the proof of Proposition 4.2 (iv) (Mayer Vietoris arguments), we conclude that:

(a) $FT = \infty (W_F(t, \epsilon) - W_F(t, \epsilon)) = \int_{M \setminus Cr(h)} \delta_F(\epsilon) - \int_{\tilde{M} \setminus Cr(\tilde{h})} \delta_{\tilde{F}}(\epsilon)$.

The left side of the above equality is zero because

$W_F(t, \epsilon) = \chi(M) \dim(W) \log \epsilon$.

In the right side of the equality the term $\int_{M \setminus Cr(h)} \delta_F(\epsilon)$ and $\int_{\hat{M} \setminus Cr(\hat{h})} \delta_{\hat{F}}(\epsilon)$ are zero and for the trivial representation and a parallel hermitian structure $\delta_{\tilde{F}} = (\alpha_{\tilde{F}} + (-1)^n \alpha_{\tilde{F}})$. Consequently $\int_{M \setminus Cr(h)} \delta_F(0) = 0$ whenever $\mu$ is parallel near critical points.

(D) follows from (4.17) by taking $\mu = \mu_0$.

Proposition 0.1 reduces to the verification that $S(M, \rho) = 0$.

Note that when $\rho$ is isomorphic to $\rho^\sharp$, hence also unimodular, the result follows from B and C.

If $\chi(M) = 0$, choose $M'$ an even dimensional manifold with nonzero Euler Poincaré characteristic and with the same fundamental group as $M$ and choose the representation $\rho' = \rho^\sharp$. By (D) we have

$0 = S(M \times M', \rho \otimes \rho^\sharp) = S(M, \rho) \cdot \chi(M') \dim(W)$

since $\rho \otimes \rho^\sharp$ is isomorphic to itself. Hence the result is true if $\chi(M) = 0$.

Suppose $\chi(M) \neq 0$. For any $M'$ with the same fundamental group as $M$ and $\rho' = \rho^\sharp$, by the same argument as in the case $\chi(M) = 0$ one concludes (from D) that

$S(M', \rho^\sharp) = -S(M, \rho) \cdot \frac{\chi(M')}{\chi(M)}$.

This implies that for any closed manifold with fundamental group $\Gamma$, $S(M, \rho) = \chi(M) \cdot F(\rho, \Gamma))$, where $F(\rho, \Gamma)$ depends only on the representation $\rho$ up to isomorphism. If $\rho$ is isomorphic to its dual $\rho^\sharp$ then by (B) and (C) $F(\rho, \Gamma) = 0$. ■

It will be shown in a forthcoming paper that in view of “harmonicity” of $S(M, \rho)$ when viewed as a real valued function on the space of representations (a complex infinite dimensional space), the function $F$ is identically zero. ■

Appendix A  Lemma of Carey-Mathai-Mishchenko
In this Appendix, we prove Lemma 1.14, using a deformation argument.

Introduce \( f_q(t) := tf_q \) and \( d_q(t) := \begin{pmatrix} d_{1,q} & tf_q \\ 0 & d_{2,q} \end{pmatrix} \) and obtain in this way a complex \((C^*, d_*(t))\).

By the same arguments as in the proof of Lemma 1.10 one concludes that \((C^*, d_*(t))\) is an algebraically acyclic, \(\zeta\)-regular complex of sF type.

Therefore, \((C^*, d_*(t))\) has a well defined torsion \(T(t) := T(C^*, d_*(t))\), given by (cf (1.21))

\[
\log T(t) = \frac{1}{2} \sum (-1)^q \log \det(d_q^*(t)d_q(t)).
\]

If \(\frac{dt}{dt} \log T(t) = 0\), then

\[
\log T(C) = \log T(1) = \log T(0) = \log T(C^1) + \log T(C^2)
\]

where for the last equality we have used that \(d_q(0) = \begin{pmatrix} d_{1,q} & 0 \\ 0 & d_{2,q} \end{pmatrix}\) and therefore \(\Delta_q(0) = \begin{pmatrix} \Delta_{1,q} & 0 \\ 0 & \Delta_{2,q} \end{pmatrix}\).

The remaining part of this Appendix is devoted to the proof of the statement

\[
\frac{dt}{dt} \log T(t) = 0.
\]

Introduce the Hodge decomposition of \(C^j, C^j_q = C^j_q^+ \oplus C^j_q^-\) (\(j = 1, 2\)). The differential \(d_{j,q}\) then have the form

\[
d_{j,q} = \begin{pmatrix} 0 & d_{j,q}^+ \\ 0 & 0 \end{pmatrix}.
\]

Further, decompose \(C_q\),

\[
(A.1) \quad C_q = C^1_q^+ \oplus C^1_q^- \oplus C^2_q^+ \oplus C^2_q^-.
\]

Then, \(d_q(t)\) can be written as

\[
d_q(t) = \begin{pmatrix} 0 & d_{1,q} & \alpha_q & \beta_q \\ 0 & 0 & \varepsilon_q & \gamma_q \\ 0 & 0 & 0 & d_{2,q} \end{pmatrix}
\]

where \(\alpha_q \equiv \alpha_q(t) = t\alpha_q, \beta_q = t\beta_q, \varepsilon_q = t\varepsilon_q\) and \(\gamma_q = t\gamma_q\). From \(d_{q+1}(t)d_q(t) = 0\) we deduce
\[(A.2) \quad d_{1,q+1} \varepsilon_q = 0; \quad \varepsilon_{q+1} d_{2,q} = 0;\]

\[(A.3) \quad d_{1,q+1} \gamma_q + \alpha_{q+1} d_{2,q} = 0.\]

As \(C^1\) and \(C^2\) are acyclic, \(d_{1,q}\) and \(d_{2,q}\) are isomorphisms, and (A.2) and (A.3) imply

\[(A.4) \quad \varepsilon_q = 0\]

\[(A.5) \quad \gamma_q = -d_{1,q+1}^{-1} \alpha_{q+1} d_{2,q}.\]

Next, let us describe the Hodge decomposition of \(C^* = C^+_q(t) \oplus C^-_q(t)\) of \((C^*, d^*_q(t)).\)

**Lemma A.1**

(i) \(C^+_q = \text{Kerd}_q = \{(x+ - d_{1,q}^{-1} \alpha_q y+, y+) \mid x+ \in C^1_q; \ y+ \in C^2_q \}\)

(ii) \(C^-_q = \text{Ker}(d_{q-1}^*) = \{(0, x-, (d_{1,q}^{-1} \alpha_q)^* x-, y-) \mid x- \in C^1_q; \ y- \in C^2_q \}\).

**Proof** The statements follow from a straightforward verification. ■

We want to compute the \(t\)-derivative of \(\log T(t) = \frac{1}{2} \sum (-1)^q \log \det (d^*_q(t) d_q(t)).\)

Notice that

\[
\frac{d}{dt} \left( d^*_q(t) d_q(t) \right) = \begin{pmatrix} 0 & 0 \\ f_q^* & 0 \end{pmatrix} \begin{pmatrix} d_{1,q} & tf_q \\ 0 & d_{2,q} \end{pmatrix} + \begin{pmatrix} d^*_{1,q} & 0 \\ tf_q^* & d^*_{2,q} \end{pmatrix} \begin{pmatrix} 0 & f_q \\ 0 & 0 \end{pmatrix}
\]

\[
= \begin{pmatrix} 0 & 0 \\ f_q^* d_{1,q} & tf_q^* f_q \end{pmatrix} + \begin{pmatrix} 0 & d^*_{1,q} f_q \\ tf_q^* f_q & 0 \end{pmatrix}
\]

\[
= \begin{pmatrix} 0 & d^*_{1,q} f_q \\ f^* d_{1,q} & 2t f_q^* f_q \end{pmatrix}.
\]

As \(f\) is a morphism of trace class (cf Definition 1.10) we conclude that \(\frac{d}{dt} d^*_q d_q(t)\) and therefore \(\frac{d}{dt} d^*_q(t) d_q(t)\) are of trace class. In view of Proposition 1.3 and the fact that \((d^*_q(t) d_q(t))^{-1}\) is bounded we deduce that \(\frac{d}{dt} (d^*_q(t) d_q(t))(d^*_q(t) d_q(t))^{-1}\) is of trace class. Therefore

\[
\frac{d}{dt} \log \det (d^*_q(t) d_q(t)) = Tr(\frac{d}{dt} (d^*_q(t) d_q(t))(d^*_q(t) d_q(t))^{-1}).
\]
With respect to the decomposition (A.1), \( D_q \) and \( D_q^{-1} \) take the form
\[
D_q^{-1} = \begin{pmatrix}
A_{11} & A_{12} & A_{13} & A_{14} \\
A_{21} & A_{22} & A_{23} & A_{24} \\
A_{31} & A_{32} & A_{33} & A_{34} \\
A_{41} & A_{42} & A_{43} & A_{44}
\end{pmatrix} ; \quad \dot{D}_q = \begin{pmatrix}
\dot{\alpha}_q & \dot{\beta}_q \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}.
\]

Thus
\[
\dot{D}_q D_q^{-1} = \begin{pmatrix}
\dot{\alpha}_q A_{31} + \dot{\beta}_q A_{41} & * & * & * \\
* & \dot{\gamma}_q A_{42} & * & * \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

and
\[
Tr(\dot{D}_q D_q^{-1}) = Tr(\dot{\alpha}_q A_{31} + \dot{\beta}_q A_{41}) + Tr(\dot{\gamma}_q A_{42}).
\]

Lemma A.2 (i) \( A_{41} = 0 \); 
(ii) \((-A_{42} d_{1,q+1}^{-1} \alpha_{q+1} + A_{43}) = d_{2,q}^{-1} \); 
(iii) \( A_{42} = -A_{43}(d_{1,q+1}^{-1} \alpha_{q+1})^* \); 
(iv) \( d_{2,q}^{-1} = A_{43}((d_{1,q+1}^{-1} \alpha_{q+1})^*(d_{1,q+1}^{-1} \alpha_{q+1}^*) + Id) \); 
(v) \( A_{42} = -d_{2,q}^{-1}(Id + (d_{1,q+1}^{-1} \alpha_{q+1}^*)(d_{1,q+1}^{-1} \alpha_{q+1}))^{-1}(d_{1,q+1}^{-1} \alpha_{q+1})^* \); 
(vi) \( \dot{\gamma}_q A_{42} = d_{2,q}^{-1}(Id + (d_{1,q+1}^{-1} \alpha_{q+1}^*)(d_{1,q+1}^{-1} \alpha_{q+1}))^{-1}(d_{1,q+1}^{-1} \alpha_{q+1})^* \).
and therefore $0 = d_{2,q}A_{41}x_+$. As $d_{2,q}$ is an isomorphism we conclude that $A_{41}x_+ = 0$.  

(ii) Take $x(0,0,0,y-) \in C_q$. By Lemma A.1, $x \in C_q^-$. Then 
\[ x = D_q^{-1}D_qx = D_q^{-1}(\beta_q y_-, \gamma_-, d_{2,q}y_-, 0) = (\ast, \ast, \ast, A_{41}\beta_q y_- + A_{42}\gamma_q y_- + A_{43}d_{2,q}y_-). \]

In view of (i), $A_{41} = 0$ and thus

\[ (A.9) \quad (A_{42} \gamma_q + A_{43}d_{2,q}) y_- = y_- . \]

Recall that $\gamma_q = -d_{1,q+1}^{-1}\alpha_{q+1}d_{2,q}$ and substitute into (A.9) to obtain (ii).

(iii) As $D_q^{-1}|_{C_q^-} = 0$ and in view of Lemma A.1, 
\[ 0 = D_q^{-1}(0, x_-, (d_{1,q+1}^{-1}\alpha_{q+1})^* x_-, 0) = (\ast, \ast, \ast, A_{41}x_- + A_{42}x_+ + A_{43}(d_{1,q+1}^{-1}\alpha_{q+1})^* x_-). \]

Thus $A_{42} + A_{43}(d_{1,q+1}^{-1}\alpha_{q+1})^* = 0$ which proves (iii).

(iv) follows from substituting (iii) into (ii).

(v) Notice that $Id + (d_{1,q+1}^{-1}\alpha_{q+1})^*(d_{1,q+1}^{-1}\alpha_{q+1}) \geq Id$ is invertible and therefore, we can solve (iv) for $A_{43}$. Substituted into (iii) we obtain (v).

(vi) Substitute $\dot{\gamma}_q = -d_{1,q+1}^{-1}\dot{\alpha}_{q+1}d_{2,q}$ into (v) to get (vi).

**Lemma A.3**

(i) $\alpha_q A_{31} + d_{1,q}A_{21} = Id$ (on $C_{1,q}^+\backslash C_{1,q}^-$),

(ii) $A_{31} = (d_{1,q}^{-1} \alpha_q)^* A_{21};$

(iii) $A_{21} = (Id + (d_{1,q}^{-1} \alpha_q)(d_{1,q}^{-1} \alpha_q)^*)^{-1}d_{1,q}^{-1};$

(iv) $\dot{\alpha}_q A_{31} = \dot{\alpha}_q(d_{1,q}^{-1} \alpha_q)^*(Id + (d_{1,q}^{-1} \alpha_q)(d_{1,q}^{-1} \alpha_q)^*)^{-1}d_{1,q}^{-1}.$

**Proof** The proof of Lemma A.3 is similar to the one of Lemma A.2.

**Lemma A.4**

(i) $\sum_q (-1)^qTr(\dot{D}_q D_q^{-1}) = 0;$

(ii) $\frac{d}{dt} \log \det T(t) = 0.$
Proof (i) Substituting Lemma A.2 (i) and (vi) as well as Lemma A.3 (iv) into (A.8) leads to

\[
Tr(\hat{D}_q D_q^{-1}) = Tr(\hat{\alpha}_q A_{31}) + 0 + Tr(\gamma_q A_{42}) \\
= Tr(\hat{\alpha}_q (d_{q,1}^{-1} \alpha_q)^* (Id + (d_{q,1}^{-1} \alpha_q)(d_{q,1}^{-1} \alpha_q)^*)^{-1} d_{q,1}^{-1}) \\
+ Tr(d_{q,1}^{-1} \hat{\alpha}_{q+1} (Id + (d_{q,1}^{-1} \alpha_q)(d_{q,1}^{-1} \alpha_q)^*)^{-1} (d_{q,1}^{-1} \alpha_{q+1})) \\
+ Tr(\hat{\alpha}_{q+1} (d_{q,1}^{-1} \alpha_q)^* (Id + (d_{q,1}^{-1} \alpha_q)(d_{q,1}^{-1} \alpha_q)^*)^{-1} d_{q,1}^{-1}) \\
+ Tr(\hat{\alpha}_{q+1} (d_{q,1}^{-1} \alpha_q)^* (Id + (d_{q,1}^{-1} \alpha_q)(d_{q,1}^{-1} \alpha_q)^*)^{-1} d_{q,1}^{-1})
\]

where for the last equality we have used the fact that \(\hat{\alpha}_q := d_{q,1}^{-1} \alpha_q\)

\[
\sum_q (-1)^q Tr(\hat{D}_q D_q^{-1}) = \sum (-1)^q Tr(\hat{\alpha}_q \eta_q^* (Id + \eta_q \eta_q^*)^{-1} d_{1,q}^{-1}) \\
- \sum (-1)^{q+1} Tr(\hat{\alpha}_{q+1} \eta_{q+1}^* (Id + \eta_{q+1} \eta_{q+1}^*) d_{1,q+1}^{-1}) = 0.
\]

(ii) follows from (i) and (A.6). \(\blacksquare\)

Appendix B Determinant class property

In this appendix, we discuss the concept of determinant class and provide examples of pairs \((M, \rho)\) which are not of determinant class.

Recall from [BFKM] that given an \(\mathcal{A}\)-Hilbert module \(\mathcal{W}\) and \(\varphi \in \mathcal{L}_\mathcal{A}(\mathcal{W})\) an operator which satisfies \(\text{Op} 1 - \text{Op} 6\), one says that \(\varphi\) is of determinant class iff

\[
\int_{0^+}^1 \ln \lambda d F_{\varphi}(\lambda) < \infty.
\]

Here \(|\varphi| = (\varphi^* \cdot \varphi)^{1/2}\).

It is not difficult to prove morphisms \(\varphi\) which are not of determinant class.

For example for \(\mathcal{A} = \mathcal{N}(\mathbb{Z})\) and \(\mathcal{W} = L^2(\mathbb{Z}) = L^2(S^1; \mathbb{C}), S^1 = \mathbb{R}/\mathbb{Z}\), the multiplication by a function \(\alpha \in L^\infty(S^1; \mathbb{C})\) defines an element \(\varphi = M_\alpha \in \mathcal{L}_\mathcal{A}(\mathcal{W})\) which satisfies \(\text{Op} 1 - \text{Op} 6\). Take \(\alpha : [0, 1] \to \mathbb{C}\) defined by \(\alpha(x) = \exp(-1/x^2)\). As \(F_{\varphi}(\lambda) = \mu(\{x \in [0, 1], |\alpha(x)| \leq \lambda\})\), where \(\mu(X)\) denotes the Lebesgue measure of the set \(X\), one can see that for \(\varphi = M_\alpha, F_{\varphi}(\lambda) = -(\log \lambda)^{1/2}\). This integral is not convergent.

Consider \((K, \tau, \rho, \mu)\) where \((K, \tau)\) is a CW complex with finitely many cells in each dimension, \(\rho\) is a representation of the group \(\pi = \pi_1(K)\) on the \(\mathcal{A}\)-Hilbert module of finite type \(\mathcal{W}\), and \(\mu\) is a Hermitian structure in the flat bundle \(\mathcal{E} \to \mathcal{K}\) induced by \(\rho\).

We say that \((K, \tau, \rho, \mu)\) is of c-determinant class (cf [BFKM]) iff the associate cochain complex of \(\mathcal{A}\)-Hilbert modules of finite type \(C^*(K, \tau, \rho, \mu)\) is of determinant class (cf [BFKM]), i.e. \(\delta_i\), or equivalently the combinatorial Laplacians \(\Delta_i^{\text{comb}}\), are of determinant class for all \(i\).
We also say that \((M,g,\rho,\mu)\), with \((M,g)\) a smooth closed Riemannian manifold and \((\rho,\mu)\) as above, is of a- determinant class if the de Rham complex \(\Omega^*(M, \rho)\) of \(A\)- Hilbert modules whose Hilbert module structure is given by the scalar products induced by \(g\) and \(\mu\), is of determinant class, i.e \(d_i\), or equivalently the Laplacians \(\Delta_i\), are of determinant class.

It was shown in [BFKM] (actually only for \(\mu\) parallel, but the same arguments remain valid in the generality presented here) that the c-determinant class property is independent of \(\tau\) and \(\mu\), the a-determinant class property is independent of \(g\) and \(\mu\) and both properties are homotopy invariant. Moreover for a compact manifold, possibly with boundary, the a-determinant class property holds iff the c-determinant class property holds. Therefore the determinant class property is a homotopy invariant for a pair \((K, \rho)\) with \(K\) a compact space of the homotopy type of a CW complex, which can be defined both analytically and combinatorially.

If \(\rho\) is a representation of \(\Gamma\), induced by a homomorphism \(\pi: \Gamma \to G\), \(G\) a countable discrete group, on the \(N(G)\)- Hilbert module \(W = L^2(\Gamma)\), then \((K, \rho)\) is of determinant class when \(G\) is residually finite or \(G\) is ameanable. Recently B.Clair [C] has verified the determinant class property when \(G\) is residually amenable group.

A representation \(\rho: \pi_1(S^1) = \mathbb{Z} \to L^\infty(\mathbb{Z})\) is determined by \(\rho(1)\). Assume that \(\rho(1)\) is the operator \(M_{1+\alpha}\) given by multiplication by \(1 + \alpha\) where \(\alpha \in L^\infty(S^1; \mathbb{C})\). Consider the cochain complex induced by \(\rho\) and the generalized triangulation \(\tau = (h, g)\) with \(h(t) = \frac{\cos(2\pi t) + 1}{2}\) and \(g\) the standard metric. As the triangulation \(\tau\) has one 0-cell \(E_0\) and one 1-cell \(E_1\), the cochain complex is of the form

\[
0 \to W \xrightarrow{\delta} W \to 0
\]

where \(\delta(E_0) = E_1 - M_{1+\alpha}E_1 = -M_\alpha E_1\). Therefore, \(\log T_{comb} = \frac{1}{2} \log \det \delta^* \delta = \frac{1}{2} \log \det \alpha^* \alpha\).

Observe that \((M, \rho)\) is of determinant class iff \(M_\alpha\) is of determinant class, therefore for \(\alpha(x) = \exp(-1/x^2)\), as indicated above \((S^1, \rho)\) is NOT of determinant class. We point out that the regular representation of \(\mathbb{Z}\) corresponds to the function \(\alpha(t) = \exp(2\pi it) - 1\).
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