Commutators of Diffeomorphisms: II.

Autor(en): **Mather, John N.**

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Commutators of Diffeomorphisms: II[1])

by JOHN N. MATHER

This paper is a sequel to [2], and we will assume the reader is familiar with the terminology and results of [2]. Our main result is the following.

THEOREM 1. *Let M be a smooth n-manifold. If $n \geqslant r \geqslant 1$, then* Diff (M, r) *is perfect.*

From Epstein's theorem [1], it then follows that we have:

COROLLARY. *Under the same hypothesis,* Diff (M, r) *is simple.*

Combining this with the result in [2], we see that the only missing differentiability class is $r=n+1$. For $r=n+1$, it is still unknown whether Theorem 1 holds.

Theorem 1 is an immediate consequence of the case when $M=\mathbf{R}^n$. The proof of Theorem 1 is very closely related to the proof of Theorem 1 in [2]. In a sense, we have turned the proof of the latter upside down.

In the final section, we give a result concerning the connectivity of Haefliger's classifying space as an application of our method. This is analogous to the result concerning the connectivity of Haefliger's classifying space we obtained in [2], but for low differentiability, rather than high differentiability.

§1. A Refinement of Theorem 1

We will actually prove a refinement of Theorem 1. Let α be a modulus of continuity, and r a positive integer.

THEOREM 2. *Suppose either of the following holds.*

a) $n > r \geqslant 1$

b) $r=n$, *α is defined on all of* $[0, \infty)$, *and there exists β, with $0<\beta<1$, such that $\alpha(tx) \leqslant t^{\beta}\alpha(x)$ for all $x \geqslant 0$ and all $t \geqslant 1$.*

Then Diff (M, r, α) *is perfect.*

Theorem 1 is an immediate consequence, since Diff $(M, r) = \bigcup_{\alpha}$ Diff(M, r, α), where the union is taken over all moduli of continuity in the case $r<n$, and all moduli of continuity satisfying the supplementary condition (b), when $r=n$.

Of course, it is enough to prove Theorem 2 in the case $M=\mathbf{R}^n$, to obtain the

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general result. We reduce the proof in §2 to the construction of certain mappings $P_{i,A}$. These mappings are constructed in subsequent sections.

§2. Strategy of the Proof

The main technical step is the construction of certain mappings $P_{i,A}$ of function spaces, and the proof of a number of properties of the $P_{i,A}$. The domain of $P_{i,A}$ is a C^1 neighborhood of the identity in the space of C^1 diffeomorphisms of $\mathbf{R}^n$ with support in $\operatorname{int} D_{i,A}$. The range of $P_{i,A}$ is the set of C^1 diffeomorphisms of $\mathbf{R}^n$ with support in $\operatorname{int} D_{i-1,A}$.

There is a close parallel between the construction of $P_{i,A}$ which we will give below and the construction of $\Psi_{i,A}$ which we already gave in [2]. Note, however, that there is already a difference: we have reversed the domain and range.

Now we list the properties we will show $P_{i,A}$ to have.

Properties of $P_{i,A}$.

1) $P_{i,A}(\mathrm{id})=\mathrm{id}$,

2) If u is in $C^{r,\alpha}$, then so is $P_{i,A}(u)$.

3) The restriction of $P_{i,A}$ to the set of C^r diffeomorphisms in its domain is continuous with respect to the C^r topologies on its domain and range.

4) If u is in the domain of $P_{i,A}$, then u is isotopic to the identity through an isotopy with support in $\operatorname{int} D_{i,A}$ and $P_{i,A}(u)$ is isotopic to the identity through an isotopy with support in $\operatorname{int} D_{i-1,A}$.

From 4), if $u \in \operatorname{dom} P_{i,A}$ and u is $C^{r,\alpha}$, then $u, P_{i,A}(u) \in \operatorname{Diff}(\mathbf{R}^n, r, \alpha)$.

5) If $u \in \operatorname{dom} P_{i,A}$ and u is $C^{r,\alpha}$ then $[u]=[P_{i,A}(u)]$ in the commutator quotient group of $\operatorname{Diff}(\mathbf{R}^n, r, \alpha)$.

6) There exists $\delta>0$, $C>0$ such that

$$\mu_{r,\alpha}(P_{i,A}(u)) \leqslant CA^{-1}\mu_{r,\alpha}(u),$$

if u is of class $C^{r,\alpha}$, lies in the domain of $P_{i,A}$, and satisfies $\mu_{r,\alpha}(u)<\delta$. Moreover, C is independent of A.

The estimate for $P_{i,A}$ given in 6) is in a sense the "inverse" of the estimate for $\Psi_{i,A}$ given in §3, (6) of [2].

In the rest of this section, we finish the proof of the Theorem 2, assuming the existence of $P_{i,A}$ satisfying (1)–(6). Consider $f \in \operatorname{Diff}(\mathbf{R}^n, r, \alpha)$ with support in $\operatorname{int} D_n$. We wish to show f is in the commutator subgroup if it is sufficiently close to id.

For any $u \in \operatorname{Diff}(\mathbf{R}^n, r, \alpha)$ with support in $\operatorname{int} D_{0,A}$ we try to define

$$u_0=A^{-1}fuA, \quad u_1=P_{n,A}(u_0), \quad u_2=P_{n-1,A}(u_1), \ldots, u_n=P_{1,A}(u_{n-1}).$$

If u and f are sufficiently close to the identity in the C^1 topology, these will actually be defined, by properties (1)–(3) of $P_{i,A}$.

It is easily seen that u_0 is conjugate to fu in Diff$(\mathbf{R}^n, r, \alpha)$. Thus, $[u_0]=[fu]$ in the commutator quotient group of Diff$(\mathbf{R}^n, r, \alpha)$. Then

$$[fu]=[u_n], \tag{$*$}$$

by (5) and the definition of the u_i.

LEMMA. *Suppose the hypotheses of Theorem 2 are satisfied. There exists A_0 such that if $A \geqslant A_0$, then for $\varepsilon > 0$ sufficiently small, $\mu_{r,\alpha}(u) \leqslant \varepsilon$ and $\mu_{r,\alpha}(f) \leqslant \varepsilon$ imply $\mu_{r,\alpha}(u_n) \leqslant \varepsilon$.*

Assuming this lemma, one can prove Theorem 2 in exactly the same way as Theorem 2 in [2] was proved there. Since there is no change in this proof, we will say nothing further about it.

Proof of the Lemma. Exactly as in the proof of the lemma in §3 of [2], we have that if $\varepsilon > 0$ is sufficiently small, and $\mu_{r,\alpha}(f) < \varepsilon$, $\mu_{r,\alpha}(u) < \varepsilon$, then $\mu_{r,\alpha}(fu) < 3\varepsilon$.

From the definition of u_0, we have $\mu_{r,\alpha}(u_0) \leqslant A^r \mu_{r,\alpha}(fu)$ and $\mu_{r,\alpha}(u_0) \leqslant A^{r-1+\beta}$ $\mu_{r,\alpha}(fu)$, if α is defined on all of $[0, \infty)$ and $\alpha(tx) \leqslant t^\beta \alpha(x)$, for $t \geqslant 1$.

From condition (6) on the mappings $P_{i,A}$, and the definition of $u_1, \ldots, u_n$, it follows that if $\varepsilon > 0$ is sufficiently small, then $\mu_{r,\alpha}(u_n) \leqslant 3C^n A^{r-n}\varepsilon$ and $\mu_{r,\alpha}(u_n) \leqslant 3C^n A^{r-n-1+\beta}\varepsilon$, if α is defined on all of $[0, \infty)$ and $\alpha(tx) \leqslant t^\beta \alpha(x)$, for $t \geqslant 1$.

Under the hypotheses of the lemma, the exponent of A is negative, so by taking A sufficiently large we may arrange that $3C^n A^{r-n} < 1$ or $3C^n A^{r-n-1+\beta} < 1$, according to the case. In either case, we have $\mu_{r,\alpha}(u_n) \leqslant \varepsilon$. Q.E.D.

§3. Construction of the Mappings $P_{i,A}$

We consider the problem: given u with support in int$D_{i,A}$, find v with support in int$D_{i-1,A}$ such that $\tau_i u$ and $\tau_i v$ are conjugate. We also wish v to satisfy an estimate of the form

$$\mu_{r,\alpha}(v) \leqslant C A^{-1} \mu_{r,\alpha}(u) \tag{1}$$

where C is a constant (independent of A). This estimate should be satisfied for u in a neighborhood of the identity. (This neighborhood may depend on A.)

Our method is similar to the method of [2, §5], where we solved the "inverse" problem. In particular, since supp$u \subset$ int$D_{i,A} \subset$ int$D_{i-1,A}$, we may and do construct h in the same way as there, provided u is sufficiently close to the identity. Let $\tilde{h}$ denote the unique diffeomorphism of $\mathbf{R}^n$ such that $\pi\tilde{h} = h\pi$ and $\tilde{h}$ is the identity on $\{x_i = 0\}$, where π denotes the projection of $\mathbf{R}^n$ on C_i.

We let B be a positive integer, which will be specified below. If h is sufficiently C^1 close to the identity, $\tilde{h}$ will be close enough to the identity for us to define diffeomorphisms $\tilde{h}_1, \ldots, \tilde{h}_B$ of $\mathbf{R}^n$ by the formulae

$$\tilde{h}_1(x) - x = \frac{1}{B}(\tilde{h}(x) - x)$$

$$\tilde{h}_2(x) - x = \frac{1}{B-1}(\tilde{h} \circ \tilde{h}_1^{-1}(x) - x)$$

$$\tilde{h}_3(x) - x = \frac{1}{B-2}(\tilde{h} \circ \tilde{h}_1^{-1} \circ \tilde{h}_2^{-1}(x) - x)$$

$$\ldots$$

$$\tilde{h}_{B-1}(x) - x = \frac{1}{2}(\tilde{h} \circ \tilde{h}_1^{-1} \circ \cdots \circ \tilde{h}_{B-2}^{-1}(x) - x)$$

$$\tilde{h}_B(x) - x = \tilde{h} \circ \tilde{h}_1^{-1} \circ \cdots \circ \tilde{h}_{B-1}^{-1}(x) - x.$$

Then $\tilde{h} = \tilde{h}_B \circ \tilde{h}_{B-1} \circ \cdots \circ \tilde{h}_1$.

Let ζ be a real C^∞ function on $\mathbf{R}$, periodic of period 1, equal to 1 in a neighborhood of the integers, equal to zero in a neighborhood of the half-integers, and satisfying $0 \leqslant \zeta \leqslant 1$ everywhere.

For $j = 1, \ldots, B$, and $k = 0, 1$, we define $\tilde{h}_{jk}$ (for $k = 0, 1$) by the formulae $\tilde{h}_{j0}(x) - x = \zeta(x_i)(\tilde{h}_j(x) - x)$ where $x = (x_1, \ldots, x_n) \in \mathbf{R}^n$, and $\tilde{h}_{j1} = \tilde{h}_j \tilde{h}_{j0}^{-1}$. These will be diffeomorphisms if h is C^1 close to id. We have $\tilde{h}_j = \tilde{h}_{j1} \tilde{h}_{j0}$ and $\tilde{h} = \tilde{h}_{B1} \tilde{h}_{B0} \tilde{h}_{B-1,1} \tilde{h}_{B-1,0} \ldots \tilde{h}_{1,1} \tilde{h}_{1,0}$.

This is the decomposition of $\tilde{h}$ we need in order to construct v.

CONSTRUCTION of v. We first construct two sequences $E_-^1, \ldots, E_-^B, E_+^1, \ldots, E_+^B$ of strips in $\mathbf{R}^n$. These are defined as follows. Let a be the least half integer $\geqslant -2A$. Let

$$E_-^j = \{x \in \mathbf{R}^n : a + 3j - 3 \leqslant x_i \leqslant a + 3j - 2\}$$

$$E_+^j = \{x \in \mathbf{R}^n : a + 3j - 3/2 \leqslant x_i \leqslant a + 3j - 1/2\}.$$

We let B be the greatest integer such that $a + 3B - 1/2 \leqslant 2A$.

In terms of increasing values of x_i, the strips occur in the following order: $E_-^1, E_+^1, E_-^2, E_+^2, \ldots, E_-^B, E_+^B$. Moreover they are disjoint, they all lie in the set $\{-2A \leqslant x_i \leqslant 2A\}$, and their sides are defined either by x_i = half-integer (the E_-^j) or x_i = integer (the E_+^j). They are squeezed as closely together as possible, compatibly with these properties.

We let $v \mid E_-^j$ be the unique diffeomorphism of E_-^j onto itself such that $v \mid E_-^j = \tilde{h}_{j0} \mid E_-^j$. We let $v \mid E_+^j$ be the unique diffeomorphism of E_+^j onto itself such that $v \mid E_+^j = \tilde{h}_{j1} \mid E_+^j$. We let

$$v \mid (\mathbf{R}^n - \bigcup_j (E_-^j \cap E_+^j)) = \mathrm{id}.$$

If u is sufficiently close to the identity this is a well defined diffeomorphism of $\mathbf{R}^n$.

Moreover, it is easily seen that $\Gamma_v^i = h$. Hence $\Gamma_v^i(\Gamma_u^i)^{-1} \in \mathcal{G}$, and it follows from the lemma in [2, §4] that $\tau_i u$ and $\tau_i v$ are conjugate in Diff$(\mathbf{R}^n, r, \alpha)$, if u is in Diff$(\mathbf{R}^n, r, \alpha)$ and sufficiently C^1 close to the identity.

This completes the construction of v. Our estimate (1) will be proved in the next section.

We set $P_{i,A}(u) = v$. Of the properties (1)–(6) of $P_{i,A}$ listed in §2, properties (1)–(3) are obvious, we may arrange for (4) to hold by replacing the domain of $P_{i,A}$ by a smaller neighborhood of id, (5) is a consequence of the fact that $\tau_i u$ and $\tau_i v$ are conjugate, and (6) is equivalent to the inequality (1) of this section, which will be proved in the next section.

§4. Estimate for v

In this section, we will complete the proof of Theorem 2 by proving the estimate (1) in §3. The proof is based on the following five estimates.

(1) If u is $C^{r,\alpha}$ and sufficiently near the identity, then

$$\mu_{r,\alpha}(\Gamma_u) \leqslant 8\mu_{r,\alpha}(u).$$

(2) If u is $C^{r,\alpha}$ and sufficiently near the identity, then

$$\mu_{r,\alpha}(h) \leqslant 3\mu_{r,\alpha}(\Gamma_u).$$

(3) There exists a constant $C_1 > 0$, independent of A, such that if u is $C^{r,\alpha}$ and sufficiently near the identity, then

$$\mu_{r,\alpha}(\tilde{h}_i) \leqslant C_1 A^{-1} \mu_{r,\alpha}(h), \qquad i = 1, \ldots, B.$$

(4) There exists a constant C_2, independent of A, such that if u is $C^{r,\alpha}$ and sufficiently close to the identity, then

$$\mu_{r,\alpha}(\tilde{h}_{i,j}) \leqslant C_2 \mu_{r,\alpha}(\tilde{h}_i), \qquad j = 0, 1$$

(5) We have

$$\mu_{r,\alpha}(v) = \max\{\mu_{r,\alpha}(\tilde{h}_{ij})\}.$$

All but one of these estimates is obvious or is in [2, §6] in slightly different guise. Thus, estimate (1) is essentially a special case of (1) in [2, §6]. Here, supp $u \subset$ int $D_{i-1,A}$, whereas there, we had only the weaker condition sup $u \subset$ int $D_{i,A}$. This explains why we may omit A from the right side of the inequality here: the width of $D_{i-1,A}$ in the ith coordinate is 4, while the width of $D_{i,A}$ is $4A$. The proof of (1) here is exactly the same as the proof of (1) in [2, §6].

Estimate (2) is exactly the same as (2) in [2, §6].

Estimate (3) is the new result. It will be proved below.

Estimate (4) is proved by the same argument that was used in Step 3 in [2, §6]. The equation (5) is obvious from the definitions.

From the estimates (1)–(5) of this section, we get that (1) of the previous section holds, with $C=24C_1C_2$.

The estimate (3) is a consequence of the following lemma. Let $\mathscr{A}$ denote the group of C^1 diffeomorphisms U of $\mathbf{R}^n$ such that $U(x)=x$ if $|x_j|\geqslant 2A$ for some $j\neq i$ or x_i is an integer. For example, $\tilde{h}$ and the $\tilde{h}_i$ are in $\mathscr{A}$.

LEMMA. *Let $0<\lambda<1$. For any $U\in\mathscr{A}$, define V by*

$$V(x)-x=\lambda(U(x)-x)$$

and let $W=UV^{-1}$ (provided V^{-1} exists, which is the case when U is sufficiently close to the identity). Then there exists $\delta>0$ (small) and $C>0$ (large) such that for any $U\in\mathscr{A}$ satisfying $\mu_{r,\alpha}(U)<\delta$, we have

$$\mu_{r,\alpha}(W)\leqslant(1-\lambda)\,\mu_{r,\alpha}(U)+C\mu_{r,\alpha}(U)^2. \tag{$*$}$$

We will prove this lemma below. First, however, we prove (3), assuming the lemma. Clearly

$$\mu_{r,\alpha}(\tilde{h}_1)=\frac{1}{B}\,\mu_{r,\alpha}(\tilde{h})=\frac{1}{B}\,\mu_{r,\alpha}(h).$$

Applying the lemma with $U=\tilde{h}$ and $\lambda=1/B$, we get

$$\mu_{r,\alpha}(\tilde{h}\circ\tilde{h}_1^{-1})\leqslant\frac{B-1}{B}\,\mu_{r,\alpha}(h)+O(\mu_{r,\alpha}(h)^2).$$

Then, it is clear that

$$\mu_{r,\alpha}(\tilde{h}_2)\leqslant\frac{1}{B}\,\mu_{r,\alpha}(h)+O(\mu_{r,\alpha}(h)^2).$$

Applying the lemma a second time, with $U=\tilde{h}\circ\tilde{h}_1^{-1}$ and $\lambda=(B-1)^{-1}$, we get

$$\begin{aligned}\mu_{r,\alpha}(\tilde{h}\circ\tilde{h}_1^{-1}\circ\tilde{h}_2^{-1})&\leqslant\frac{B-2}{B-1}\,\mu_{r,\alpha}(\tilde{h}\circ\tilde{h}_1^{-1})+O(\mu_{r,\alpha}(\tilde{h}\circ\tilde{h}_1^{-1})^2)\\&\leqslant\frac{B-2}{B}\,\mu_{r,\alpha}(h)+O(\mu_{r,\alpha}(h)^2).\end{aligned}$$

Then, it is clear that $\mu_{r,\alpha}(\tilde{h}_3)\leqslant(1/B)\,\mu_{r,\alpha}(h)+O(\mu_{r,\alpha}(h)^2)$.

Continuing in this way, we see that we have

$$\mu_{r,\alpha}(\tilde{h}_i) \leqslant \frac{1}{B}\mu_{r,\alpha}(h) + O(\mu_{r,\alpha}(h)^2)$$

for $i=1, 2, \ldots, B$. However, it is clear from the definition of B that $B \geqslant \frac{1}{2}A$, so we get the estimate (3).

Proof of the Lemma. We give different proofs depending on whether $r=1$ or $r>1$. If f is a mapping of $\mathbf{R}^n$ into itself, we define

$$\nu_r(f) = \sup_{x \in \mathbf{R}^n} \|D^r f(x)\|.$$

Case $r>1$. We write $R_{f,g}$ for the sum of the "other terms" in formula (2) in §2 of [2]. Thus,

$$D^r(f \circ g) = (D^r f \circ g)\cdot(Dg)^r + (Df \circ g)\cdot D^r g + R_{f,g}. \tag{6}$$

If f and g are C^r, then $R_{f,g}$ is C^1 and there exists $\delta>0$ and $C>0$ such that if $f, g \in \mathscr{A}$ and $\nu_r(f)$, $\nu_r(g) < \delta$, then

$$\nu_1(R_{f,g}) \leqslant C\nu_r(f)\,\nu_r(g).$$

Applying (6) to $g=f^{-1}$, we get

$$D^r(f^{-1}) = -((Df)^{-1} \circ f^{-1})\cdot(D^r f \circ f^{-1})\cdot((Df)^{-1} \circ f^{-1})^r + R_f, \tag{7}$$

where there exists $\delta>0$ and $C>0$ such that if $f \in \mathscr{A}$ and $\nu_r(f) < \delta$, then

$$\nu_1(R_f) \leqslant C\nu_r(f)^2.$$

Then

$$\begin{aligned} D^r W &= (D^r U \circ V^{-1})\cdot(DV^{-1})^r + (DU \circ V^{-1})\cdot D^r V^{-1} + R_{U,1} \\ &= (D^r U \circ V^{-1}) - \lambda(D^r U \circ V^{-1}) + S_U + R_{U,2} \end{aligned}$$

where

$$\begin{aligned} S_U = {} & (D^r U \circ V^{-1})\cdot(DV^{-1})^r - D^r U \circ V^{-1} \\ & + (D^r V \circ V^{-1} - ((DU \circ V^{-1})\cdot((DV)^{-1} \circ V^{-1})\cdot(D^r V \circ V^{-1})\cdot((DV)^{-1} \circ V^{-1})^r)) \end{aligned}$$

and $R_{U,i}$ $(i=1, 2)$ has the property that there exists $\delta>0$ and $C>0$ such that if $U \in \mathscr{A}$ and $\nu_r(U) < \delta$, then $\nu_1(R_{U,i}) < C\nu_r(U)^2$.
Then it is easily seen that there exist $\delta>0$ and $C>0$, such that if $U \in \mathscr{A}$ and $\mu_{r,\alpha}(U) < \delta$, we have

$$\mu_\alpha(S_U + R_{U,2}) \leqslant C\mu_{r,\alpha}(U)^2.$$

The lemma (in the case $r>1$) follows immediately.

Case $r=1$. We have

$$DW=(DU\circ V^{-1})\cdot D(V^{-1})=(DU\circ V^{-1})\cdot((DV)^{-1}\circ V^{-1})=(DU\cdot(DV)^{-1})\circ V^{-1}. \tag{8}$$

Then

$$\begin{aligned}(DV)^{-1}&=(I+(DV-I))^{-1}=I-(DV-I)+(DV-I)^2-\cdots\\&=I-\lambda(DU-I)+\lambda^2(DU-I)^2-\cdots.\end{aligned}$$

Therefore

$$DU\cdot(DV)^{-1}=I+(1-\lambda)(DU-I)+a_2(DU-I)^2+a_3(DU-I)^3+\cdots \tag{9}$$

where $a_2z^2+a_3z^3+\cdots$ is a convergent power series (for $|z|<\lambda^{-1}$). The lemma, in the case $r=1$, follows immediately from formulas (8) and (9).

§5. Application to Haefliger's Classifying Space

This is just like §7 of [2]. We get that $F\Gamma_n^r$ is $(n+1)$-connected if $n\geqslant r\geqslant 1$. Likewise $F\Gamma_n^{r,\alpha}$ is $(n+1)$-connected under the hypotheses of Theorem 2. These assertions follow in exactly the same way from the main results of this paper as the assertions in §7 of [2] followed from the main results of [2], so we will not repeat the proofs here.

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Dept. of Mathematics
Harvard University
1 Oxford Street
Cambridge, Mass. 02138
U.S.A.

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