

Title	A localization algorithm for $\mathbb{C}[[x]]$ -modules and its application (Microlocal Analysis and PDE in the Complex Domain)
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Citation	数理解析研究所講究録 (2000), 1159: 74-80
Issue Date	2000-06
URL	http://hdl.handle.net/2433/64211
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

A localization algorithm for D -modules and its application

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First, we review the localization algorithm given in a joint paper with N. Takayama (Kobe) and U. Walther (Minnesota/MSRI) [6] with slightly different reasoning of the correctness. The latter part applies this algorithm to the problem of finding the annihilator ideal of some elementary functions.

1 A localization algorithm

We work entirely in the algebraic category. Put $X = \mathbb{C}^n$ and $Y = \{x = (x_1, \dots, x_n) \in X \mid f(x) = 0\}$ with a nonzero polynomial $f \in \mathbb{C}[x]$. We denote by \mathcal{D}_X the sheaf of algebraic differential operators on X . Let \mathcal{M} be a coherent left \mathcal{D}_X -module on X such that \mathcal{M} is holonomic on $X \setminus Y$. Then Kashiwara ([2]) proved that the localization $\mathcal{M}[1/f] := \mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{O}_X[1/f]$ of \mathcal{M} by f is a holonomic \mathcal{D}_X -module on X , where \mathcal{O}_X is the sheaf of regular functions on X . (In fact he proved this fact in the analytic category, which is a stronger statement.) Here we remark that starting from an algebraic (i.e., a \mathcal{D}_X -) module, the localization is the same both in the algebraic and in the analytic category. More precisely, if we denote by $\mathcal{O}_X^{\text{an}}$ and $\mathcal{D}_X^{\text{an}}$ the sheaves of holomorphic functions and of holomorphic differential operators on X respectively, then we have an isomorphism

$$\mathcal{O}_X^{\text{an}}[1/f] \otimes_{\mathcal{O}_X^{\text{an}}} (\mathcal{D}_X^{\text{an}} \otimes_{\mathcal{D}_X} \mathcal{M}) \simeq \mathcal{D}_X^{\text{an}} \otimes_{\mathcal{D}_X} \mathcal{M}[1/f].$$

Our claim is that $\mathcal{M}[1/f]$ is computable if the input, i.e. both \mathcal{M} and f are defined over a computable subfield of \mathbb{C} (e.g. over \mathbb{Q}).

Now let us explain our algorithm. Introducing an auxiliary variable t , put

$$W := \{(t, x) \in \mathbb{C} \times X \mid tf(x) = 1\}$$

and let $\iota : W \rightarrow \mathbb{C}^{n+1}$ be the natural embedding. Let $p : W \rightarrow X$ be the projection $p(t, x) = x$ and $\varphi : X \setminus Y \rightarrow W$ be the isomorphism defined by $\varphi(x) = (1/f(x), x)$. Let

$j : X \setminus Y \longrightarrow X$ be the natural embedding. Thus we have a commutative diagram

$$\begin{array}{ccc} W & \xrightarrow{\iota} & \mathbb{C} \times X \\ \varphi \uparrow & & p \downarrow \\ X \setminus Y & \xrightarrow{j} & X \end{array}$$

Then by using the integration functor (in the algebraic category) we get

$$\mathcal{M}[1/f] = \int_j j^{-1} \mathcal{M} = \int_p \int_\iota \int_\varphi j^{-1} \mathcal{M}.$$

(See e.g. [7].) Our algorithm simply performs the rightmost successive integration step by step. (For the sake of simplicity we describe the algorithm in the case where \mathcal{M} is generated by one element.) We denote by $D_n = D_n(\mathbb{C})$ the Weyl algebra on n variables x with coefficients in \mathbb{C} . Then we can regard D_n as the set of global sections $\Gamma(X, \mathcal{D}_X)$ of \mathcal{D}_X . In general, for a left coherent \mathcal{D}_X -module \mathcal{M} , its global sections $M := \Gamma(X, \mathcal{M})$ is a finitely generated left D_n -module and its correspondence yields an equivalence of the category of left coherent \mathcal{D}_X -modules on X and that of finitely generated left D_n -modules since X is affine. The converse correspondence is given by the sheafification (or the ‘localization’) $\mathcal{M} = \mathcal{D}_X \otimes_{D_n} M$.

Algorithm-Theorem 1

Input: A polynomial $f \in \mathbb{Q}[x]$ and a finite subset $\{P_1, \dots, P_r\}$ of $D_n(\mathbb{Q})$ which generates a left ideal I of D_n such that the sheafification \mathcal{M} of $M := D_n/I$ is holonomic on $X \setminus Y$.

(1)

- (a) Put $\vartheta_i := \partial_i - t^2 f_i \partial_t$ with $f_i := \partial f / \partial x_i$, $\partial_i := \frac{\partial}{\partial x_i}$, and $\partial_t := \frac{\partial}{\partial t}$.
- (b) Compute $\tilde{P}_i := P_i(x, \vartheta_1, \dots, \vartheta_n)$. More precisely, Writing P_i in the normal form (i.e. make the derivations first and then multiply by polynomials) and substitute ϑ_i for ∂_i in P_i . (Note that $\vartheta_1, \dots, \vartheta_n$ commute with one another.)
- (c) Let J be the left ideal of D_{n+1} generated by $\tilde{P}_1, \dots, \tilde{P}_r$ and $1 - tf(x)$ and put $N := D_{n+1}/J$

(2) Compute $N/\partial_t N$ as left D_n -module as follows:

- (a) Let G be an involutive basis of J with respect to the weight vector

$$w = (1, 0, \dots, 0; -1, 0, \dots, 0)$$

for $(t, x_1, \dots, x_n; \partial_t, \partial_1, \dots, \partial_n)$.

- (b) Compute a generator $b(s)$ of the ideal

$$\{b(s) \in \mathbb{C}[s] \mid b(t\partial_t) + Q \in J \text{ with some } Q \in D_{n+1} \text{ such that } \text{ord}_w(Q) \leq -1\}$$

of $\mathbb{C}[s]$, where $\text{ord}_w(Q)$ denotes the maximum weight of the terms of Q with respect to the weight w . $b(s)$ can be computed by eliminating x and $\partial_1, \dots, \partial_n$ from the highest weight parts (w.r.t. w) of elements of G . Find the largest nonnegative integer root k_1 of $b(s) = 0$. If there is no nonnegative integer root, then we have $M[1/f] = 0$.

(c) In general, for $P \in D_{n+1}$, there exist unique $Q \in D_{n+1}$ and $R \in D_n[t]$ such that

$$P = \partial_t Q + R.$$

Let us denote this R by $R = \rho(P)$. Then R can be regarded as a relation among the residue classes $\bar{1}, \bar{t}, \bar{t}^2, \dots$ in $N/\partial_t N$. Let L be the left D_n -submodule of $D_n + tD_n + \dots + t^{k_1}D_n \simeq D_n^{k_1+1}$ generated by

$$\{\rho(t^j P) \mid P \in G, \text{ord}_w(P) + j \leq k_1\}.$$

Then L defines a system of linear differential equations for $\bar{1}, \bar{t}, \dots, \bar{t}^{k_1}$ in $N/\partial_t N$.

(d) Eliminate $\bar{1}, \bar{t}, \dots, \bar{t}^{k_1-1}$ from L and obtain an ideal L_0 of D_n which annihilates \bar{t}^{k_1} .

Output: $\mathcal{M}[1/f]$ is isomorphic to the sheafification of D_n/L_0 . More precisely the ideal L_0 is the annihilator ideal of $f^{-k_1-2}u$, which generates $M[1/f]$ (here u is the residue class of 1 in M).

Proof: First we have

$$j^{-1}\mathcal{M} = \mathcal{D}_X[1/f]/(\mathcal{D}_X[1/f]P_1 + \dots + \mathcal{D}_X[1/f]P_r),$$

which is a holonomic $\mathcal{D}_X[1/f]$ -module. Let A_W be the subring of D_{n+1} generated by $\mathbb{C}[t, x]$ and $\vartheta_1, \dots, \vartheta_n$. Then $A_W(tf(x) - 1)$ is a two-sided ideal of A_W and $D_W := A_W/A_W(1 - tf(x))$ is the set of global sections of the sheaf \mathcal{D}_X of algebraic differential operators on W (note that W is affine). Then we have an isomorphism (see [4])

$$\int_{\varphi} j^{-1}\mathcal{M} \simeq \mathcal{D}_W/(\mathcal{D}_W\tilde{P}_1 + \dots + \mathcal{D}_W\tilde{P}_r).$$

Next, the integration along ι is nothing but the so-called Kashiwara equivalence and in view of Proposition A.1 of [4] we have

$$\int_{\iota} \int_{\varphi} j^{-1}\mathcal{M} = \mathcal{D}_{C \times X} \otimes_{D_{n+1}} N,$$

which is a holonomic $\mathcal{D}_{C \times X}$ -module. Next by the definition of the integration we have

$$\int_p N = N/\partial_t N.$$

Let $\mathcal{F}(J)$ be the partial Fourier transform of J with respect to t , which is the ring isomorphism of D_{n+1} that sends t to $-\partial_t$, ∂_t to t , and leaves x_i, ∂_i unchanged. Put $\mathcal{F}(N) := D_{n+1}/\mathcal{F}(J)$. Then we have

$$N/\partial_t N \simeq \mathcal{F}(N)/t\mathcal{F}(N)$$

and the step (2) is nothing but (the Fourier transform of) the restriction algorithm (Theorem 5.7) of [5]. Note that $N/\partial_t N$ is a holonomic D_n -module since N is holonomic on $\mathbb{C} \times X$. Thus we have proved that

$$M[1/f] \simeq N/\partial_t N \simeq (D_n)^{k_1+1}/L. \quad (1)$$

Let us describe the first isomorphism of (1) more explicitly. First note the isomorphism

$$N/\partial_t N \simeq D_{n+1}/(J + \partial_t D_{n+1}).$$

For an arbitrary $P \in D_{n+1}$, there exist unique $R_0, R_1, \dots \in D_n$ and $S \in D_{n+1}$ such that

$$P = \sum_{j \geq 0} t^j R_j(x, \vartheta_1, \dots, \vartheta_n) + \partial_t S. \quad (2)$$

Then we define

$$\begin{aligned} \psi(P) &:= \sum_{j \geq 0} f^{-j-2} R_j(x, \partial_1, \dots, \partial_n) u \\ &= \sum_{j \geq 0} R_j \left(x, \partial_1 + (j+2) \frac{f_1}{f}, \dots, \partial_n + (j+2) \frac{f_n}{f} \right) f^{-j-2} u \in M[1/f]. \end{aligned}$$

Note that since the commutation relation of x_i and ϑ_i is the same as that of x_i and ∂_i , the above (non-commutative) substitution makes sense irrespective of the actual expression of R_j . This defines a left D_n -homomorphism $\psi : D_{n+1} \rightarrow M[1/f]$. In fact, we have $\psi(\partial_i P) = \partial_i \psi(P)$ since

$$\begin{aligned} \psi(\partial_i t^j R_j(x, \vartheta_1, \dots, \vartheta_n)) &= \psi(t^j (\vartheta_i + t^2 f_i \partial_t) R_j(x, \vartheta_1, \dots, \vartheta_n)) \\ &= \psi(t^j (\vartheta_i - (j+2) t f_i) + \partial_t t^{j+2} f_i) R_j(x, \vartheta_1, \dots, \vartheta_n) \\ &= \psi(t^j (\vartheta_i - (j+2) t f_i) R_j(x, \vartheta_1, \dots, \vartheta_n)) \\ &= f^{-j-2} \partial_i R_j(x, \partial_1, \dots, \partial_n) u - (j+2) f^{-j-3} f_i R_j(x, \partial_1, \dots, \partial_n) \\ &= \partial_i f^{-j-2} R_j(x, \partial_1, \dots, \partial_n) u. \end{aligned}$$

Since P_1, \dots, P_r annihilate u , we get

$$\psi(t^j \tilde{P}_i) = f^{-j-2} P_i(x, \partial_1, \dots, \partial_n) u = 0.$$

It is easy to see that $\psi(t^j(1 - tf(x))) = 0$. Hence $J + \partial_t D_{n+1}$ is contained in the kernel of ψ .

Conversely, suppose that P of the form (2) is contained in the kernel of ψ . Then there exist $Q_1(t, x, \partial), \dots, Q_r(t, x, \partial) \in D_n[t]$ such that

$$\sum_{j \geq 0} f^{-j} R_j(x, \partial_1, \dots, \partial_n) = \sum_{i=1}^r f^2 Q_i(1/f, x, \partial_1, \dots, \partial_n) P_i(x, \partial_1, \dots, \partial_n)$$

holds in $D_n[1/f]$. Then the Hilbert Nullstellensatz assures that

$$\sum_{j \geq 0} t^j R_j(x, \vartheta_1, \dots, \vartheta_n) - \sum_{i=1}^r f^2 Q_i(t, x, \vartheta_1, \dots, \vartheta_n) P_i(x, \vartheta_1, \dots, \vartheta_n) \in (1 - tf(x)) D_{n+1}$$

since $1 - tf(x)$ is irreducible. Noting $(1 - tf(x))\vartheta_i \in D_{n+1}(1 - tf(x))$, we conclude that $P \in J + \partial_t D_{n+1}$. Thus ψ gives the first isomorphism of (1). This implies that $M[1/f]$ is generated by $f^{-2}u, \dots, f^{-k_1-2}u$, and hence only by $f^{-k_1-2}u$. This completes the proof.

2 An application to holonomic functions

Let u be a (possibly multivalued) analytic function defined on \mathbb{C}^n minus an algebraic set. Suppose that u is hyperexponential ([1]); i.e., $g_i := \partial_i u / u$ is a rational function for any $i = 1, \dots, n$. For example, if f_1, \dots, f_m, g are rational functions and $\alpha_1, \dots, \alpha_m$ are complex numbers, then

$$u = f_1^{\alpha_1} \dots f_m^{\alpha_m} \exp(g(x))$$

is a hyperexponential function. Then we can find the annihilator ideal

$$\text{Ann}(u) := \{P \in D_n \mid Pu = 0\}$$

of u exactly by applying the localization algorithm.

Algorithm-Theorem 2

Input: Let u be a (possibly) multi-valued analytic function such that $g_i := \partial_i u / u \in \mathbb{Q}(x)$ for any $i = 1, \dots, n$.

- (1) Let $g \in \mathbb{Q}[x]$ be the least common multiple of the denominators of g_1, \dots, g_n . Let $f(x)$ be the square-free part of g .
- (2) Put $I := D_n(g\partial_1 - gg_1) + \dots + D_n(g\partial_n - gg_n)$.
- (3) Apply Algorithm-Theorem 1 with input D_n/I and f , and let L_0 be the output ideal with the integer k_1 .

(4) Compute the ideal quotient

$$L_1 := L_0 : (f^{k_1+2}) = \{P \in D_n \mid Pf^{k_1+2} \in L_0\}$$

by syzygy computation through Gröbner basis.

Output: $L_1 = \text{Ann}(u)$. In particular, u is a holonomic function, i.e., $D_n/\text{Ann}(u)$ is a holonomic system.

Proof: Put $\mathcal{L} := \mathcal{D}_X u$, which is a sheaf of multivalued analytic functions, and define the sheaf

$$\text{Ann}(u) := \{P \in \mathcal{D}_X \mid Pu = 0\},$$

which is the sheafification of $\text{Ann}(u)$. Then we have $\mathcal{L} \simeq \mathcal{D}_X/\text{Ann}(u)$. Let \mathcal{M} be the sheafification of $M = D_n/I$. It is easy to see that \mathcal{M} is a holonomic system of rank one outside of $Y := \{x \in X = \mathbb{C}^n \mid f(x) = 0\}$. This implies that the two sheaves \mathcal{M} and \mathcal{L} coincide on $X \setminus Y$. Hence in view of the Hilbert Nullstellensatz, we have

$$\mathcal{M}[1/f] = \mathcal{L}[1/f]. \quad (3)$$

By Algorithm-Theorem 1, $M[1/f]$ is generated by $f^{-k_1-2}\bar{1}$ whose annihilator ideal is L_0 . Hence L_1 is the annihilator ideal of $\bar{1}$ in $M[1/f]$.

On the other hand, since \mathcal{L} is a set of analytic functions, the natural homomorphism

$$\mathcal{L} \longrightarrow \mathcal{L}[1/f] = \mathcal{O}_X[1/f] \otimes_{\mathcal{O}_X} \mathcal{L}$$

induced by the embedding of \mathcal{O}_X to $\mathcal{O}_X[1/f]$ is injective. In fact, this follows from the fact that $f \cdot : \mathcal{L} \longrightarrow \mathcal{L}$ is injective. By the isomorphism (3), $\bar{1} \in M[1/f]$ corresponds to $u \in \mathcal{L}$, and its annihilator ideal in $\mathcal{L}[1/f]$ is given by L_1 . Since \mathcal{L} is a submodule of $\mathcal{L}[1/f]$, the annihilator ideal of u in $\mathcal{L}[1/f]$ coincides with that in \mathcal{L} . This implies that $L_1 = \text{Ann}(u)$. This completes the proof.

Example 1 Put $X := \{(x, y, z) \in \mathbb{C}^3\}$ and $f(x, y, z) := x^3 - y^2z^2$. Let us find the annihilator ideal of the function $u := \exp(1/f(x))$. The following computations were performed by computer algebra systems kan/sm1 [9] and Risa/Asir [8] which are connected via open xxx protocol [10]. First let I be the left ideal of D_3 generated by

$$f^2\partial_x - f_x, \quad f^2\partial_y - f_y, \quad f^2\partial_z - f_z$$

with $\partial_x = \partial/\partial x$, $f_x = \partial f/\partial x$, and so on. By computing the characteristic variety $\text{Char}(M)$ of $M := D_3/I$ (see [3] for an algorithm) and by decomposing it to prime (or primary) factors, we know that

$$\text{Char}(M) \supset \{(x, y, z; \xi, \eta, \zeta) \in T^*\mathbb{C}^3 \mid x = y = 0\} \cup \{x = z = 0\}.$$

In particular, M is not holonomic on \mathbb{C}^3 . Next by using Algorithm-Theorem 1 with I and f as input, we know that $\text{Ann}(u)$ is generated by the following eight operators:

$$\begin{aligned} & 36y\partial_y - 36z\partial_z, \\ & -24yz^2\partial_x - 36x^2\partial_y, \\ & -24y^2z\partial_x - 36x^2\partial_z, \\ & -24z^3\partial_x\partial_z - 36x^2\partial_y^2 - 24z^2\partial_x, \\ & 24x^4\partial_x^2 + 72x^3z\partial_x\partial_z + 54x^2z^2\partial_z^2 + 96x^3\partial_x + 162x^2z\partial_z + 72\partial_x, \\ & 36y^2z^3\partial_z - 24x^4\partial_x - 72x^3z\partial_z - 72, \\ & -36yz^4\partial_z^2 + 24x^4\partial_x\partial_y + 72x^3z\partial_y\partial_z - 108yz^3\partial_z + 72\partial_y, \\ & 36z^5\partial_z^3 - 24x^4\partial_x\partial_y^2 - 72x^3z\partial_y^2\partial_z + 216z^4\partial_z^2 + 216z^3\partial_z - 72\partial_y^2. \end{aligned}$$

We can verify that $D_3/\text{Ann}(u)$ is in fact holonomic and that I is contained in $\text{Ann}(u)$.

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