CONSTRUCTIBLE EXPONENTIAL FUNCTIONS,
MOTIVIC FOURIER TRANSFORM AND TRANSFER
PRINCIPLE

by

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1. Introduction

In our previous work [8], we laid general foundations for motivic integration of constructible functions. One of the most salient features of motivic constructible functions is that they form a class which is stable by direct image and that motivic integrals of constructible functions depending on parameters are constructible as functions of the parameters. Though motivic constructible functions as defined in [8] encompass motivic analogues of many functions occurring in integrals over non archimedean local fields, one important class of functions was still missing in the picture, namely motivic analogues of non archimedean integrals of the type

$$\int_{\mathbb{Q}_p^n} f(x) \Psi(g(x)) |dx|,$$

with $\Psi$ a (non trivial) additive character on $\mathbb{Q}_p$, $f$ a $p$-adic constructible function and $g$ a $\mathbb{Q}_p$-valued definable function on $\mathbb{Q}_p^n$, and their parametrized versions, functions of the type

$$\lambda \mapsto \int_{\mathbb{Q}_p^n} f(x, \lambda) \Psi(g(x, \lambda)) |dx|,$$

where $\lambda$ runs over, say $\mathbb{Q}_p^m$, and $f$ and $g$ are now functions on $\mathbb{Q}_p^{m+n}$. Needless to say, such kind of integrals are ubiquitous in harmonic analysis over non archimedean local fields, $p$-adic representation Theory and the Langlands Program.

One of the purposes of the present paper is to fill this gap by extending the framework of [8] in order to include motivic analogues of exponential integrals of the above type. Once this is done one is able to develop a natural Fourier transform and to prove various forms of Fourier inversion. Another interesting feature of our formalism is that it makes possible to state and prove a general transfer principle for integrals over non archimedean local fields, allowing to transfer identities between functions defined by integrals over fields of characteristic zero to fields of characteristic $p$, when the residual characteristic is large enough, and vice versa. It
should be emphasized that our statement holds for quite general functions defined by integrals depending on valued field variables. One should keep in mind that there is no meaning in comparing values of individual parameters in the integrals or the integrals themselves between characteristic zero and characteristic \( p \). Our transfer principle, which can be considered as a wide generalization of the classical Ax-Kochen-Eršov result, should have a wide range of applications to \( p \)-adic representation Theory and the Langlands Program, in particular to various forms of the Fundamental Lemma. For instance, it applies typically to the integrals occurring in Jacquet-Ye conjecture \([24]\), now a theorem thanks to work of Ngô \([27]\) over functions fields and Jacquet \([25]\) in general.

Let us now review the content of the paper in more detail. In section 3 we enlarge our Grothendieck rings in order to add exponentials. In fact it is useful to consider not only exponentials of functions with values in the valued field, but also exponentials of functions with values in the residue field. This is performed in a formal way by replacing the category \( \text{RDef}_S \) considered in \([8]\) - consisting of certain objects \( X \to S \) - by a larger category \( \text{RDef}^\exp_S \) consisting of the same \( X \to S \) together with functions \( g \) and \( \xi \) on \( X \) with values in the valued field, resp. the residue field. We define a Grothendieck ring \( K_0(\text{RDef}^\exp_S) \) generated by classes of objects \( (X,g,\xi) \) modulo certain relations. Here we have to add some new relations to the classical ones already considered in \([8]\). When \( X \to S \) is the identity, the class of \( (X,g,0) \), resp. \( (X,0,\xi) \), corresponds to the exponential of \( g \), resp. the exponential of \( \xi \). One defines the ring \( \mathcal{C}(S)^\exp \) of motivic exponential functions on \( S \) by tensoring \( K_0(\text{RDef}^\exp_S) \) with the ring \( \mathcal{P}(S) \) of constructible Presburger functions on \( S \). We are then able to state our main results on integration of exponential functions in section 4. In particular we show that integrals with parameters of functions in \( \mathcal{C}^\exp \) still lie in \( \mathcal{C}^\exp \). We first directly construct integrals of exponential functions in relative dimension 1 in section 5 and then perform the general construction in section 6. As was the case in \([8]\), extensive use is made of the Denef-Pas cell decomposition Theorem. Though some parts of our constructions and proofs are quite similar to what we performed in \([8]\), or sometimes even follow directly from \([8]\), other require new ideas and additional work specific to the exponential setting. As a first application, we develop in section 7 the fundamentals of a motivic Fourier transform. More precisely, there are two Fourier transforms, the first one over residue field variables and the second one, which is more interesting, over valued field variables. Calculus with our valued field Fourier transform is completely similar to the usual one. Using convolution, we define motivic Schwartz-Bruhat functions, and we show that the valued field Fourier transform is involutive on motivic Schwartz-Bruhat functions. We finally deduce Fourier inversion for integrable functions with integrable Fourier transforms. In the following section 8 we move to the \( p \)-adic setting, defining the \( p \)-adic analogue of \( \mathcal{C}(S)^\exp \) and proving stability under integration with parameters of these \( p \)-adic constructible exponential functions. Such a result is the natural extension to the exponential context of Denef’s fundamental result on stability of \( p \)-adic constructible functions under integration with respect to parameters. This
result of Denef greatly influenced our work [8] and the present one. It has been later
generalized to the subanalytic case by the first author in [4] and [5]. In section 9 we loop the loop by showing that motivic integration of constructible exponential functions commutes with specialization to the corresponding non archimedean ones, when the residue characteristic is large enough. Finally, we end the paper by proving our fundamental transfer Theorem, a form of which was already stated in [9] when there is no exponential. Let us note that in their recent paper [22] Hrushovski and Kazhdan have also considered integrals of exponentials.

Some of the results in this paper have been announced in [10].

2. Preliminaries

2.1. Definable subassignments and constructible functions. — Let us start by recalling briefly some definitions and constructions from [8], cf. also [6], [7]. We fix a field $k$ of characteristic zero and we consider for any field $K$ containing $k$ the field of Laurent series $K((t))$ endowed with its natural valuation

$$\text{ord} : K((t))^\times \longrightarrow \mathbb{Z}$$

and with the angular component mapping

$$\text{ac} : K((t)) \longrightarrow K,$$

defined by $\text{ac}(x) = xt^{-\text{ord}(x)} \mod t$ if $x \neq 0$ and $\text{ac}(0) = 0$. We use the Denef-Pas language $L_{\text{DP}, P}$ which is a 3-sorted language

$$(L_{\text{Val}}, L_{\text{Res}}, L_{\text{Ord}}, \text{ord}, \text{ac})$$

with sorts corresponding respectively to valued field, residue field and value group variables. The languages $L_{\text{Val}}$ and $L_{\text{Res}}$ are equal to the ring language $L_{\text{Rings}} = \{+, -, \cdot, 0, 1\}$, and for $L_{\text{Ord}}$ we take the Presburger language

$$(L_{\text{PR}} = \{+, -, 0, 1, \leq\} \cup \{\equiv_n \mid n \in \mathbb{N}, \ n > 1\},$$

with $\equiv_n$ the equivalence relation modulo $n$. Symbols $\text{ord}$ and $\text{ac}$ will be interpreted respectively as valuation and angular component, so that $(K((t)), K, \mathbb{Z})$ is a structure for $L_{\text{DP}, P}$. We shall also add constants symbols in the Val, resp. Res, sort, for every element of $k((t))$, resp. $k$.

Let $\varphi$ be a formula in the language $L_{\text{DP}, P}$ with respectively $m$, $n$ and $r$ free variables in the various sorts. For every $K$ in $F_k$, the category of fields containing $k$, we denote by $h_\varphi(K)$ the subset of

$$h[m, n, r](K) := K((t))^m \times K^n \times \mathbb{Z}^r$$

consisting of points satisfying $\varphi$. We call the assignment $K \mapsto h_\varphi(K)$ a definable subassignment and we define a category $\text{Def}_k$ whose objects are definable subassignments.

More generally for $S$ in $\text{Def}_k$, we denote by $\text{Def}_S$ the category of objects of $\text{Def}_k$ over $S$. We denote by $\text{RDef}_S$ the subcategory of $\text{Def}_S$ consisting of definable
subassignments of $S \times h[0, n, 0]$, for variable $n$, and by $K_0(\text{RDef}_S)$ the corresponding Grothendieck ring.

We consider the ring

$$A = \mathbb{Z} \left[ L, L^{-1}, \left( \frac{1}{1 - L^{-i}} \right)_{i > 0} \right]$$

and the subring $\mathcal{P}(S)$ of the ring of functions from the set of points of $S$ to $A$ generated by constant functions, definable functions $S \to \mathbb{Z}$ and functions of the form $L^\beta$ with $\beta$ definable $S \to \mathbb{Z}$. If $Y$ is a definable subassignment of $S$, we denote by $1_Y$ the function in $\mathcal{P}(S)$ with value 1 on $Y$ and 0 outside. We denote by $\mathcal{P}^0(S)$ the subring of $\mathcal{P}(S)$ generated by such functions and by the constant function $L$. There is a morphism $\mathcal{P}^0(S) \to K_0(\text{RDef}_S)$ sending $1_Y$ to the class of $Y$ and sending $L$ to the class of $h[0, 1, 0]$. Finally we define the ring of constructible motivic functions on $S$ by

$$C(S) := K_0(\text{RDef}_S) \otimes_{\mathcal{P}^0(S)} \mathcal{P}(S).$$

To any algebraic subvariety $Z$ of $\mathbb{A}^m_{k[t]}$, we assign the definable subassignment $h_Z$ of $h[m, 0, 0]$ given by $h_Z(K) = Z(K((t)))$. The Zariski closure of a subassignment $S$ of $h[m, 0, 0]$ is the intersection $W$ of all algebraic subvarieties $Z$ of $\mathbb{A}^m_{k[t]}$ such that $S \subset h_Z$. We set $\dim S := \dim W$. More generally, if $S$ is a subassignment of $h[m, n, r]$, we define $\dim S$ to be $\dim p(S)$ with $p$ the projection $h[m, n, r] \to h[m, 0, 0]$. One proves, using results of [29] and [20], that two isomorphic objects in $\text{Def}_k$ have the same dimension. For every non negative integer $d$, we denote by $C \leq d(S)$ the ideal of $C(S)$ generated by the characteristic functions $1_Z$ of definable subassignments $Z$ of $S$ with $\dim Z \leq d$. We set $C(S) = \bigoplus_d C^d(S)$ with $C^d(S) := C^{\leq d}(S)/C^{\leq d-1}(S)$.

In [8], we defined, for $k$ a field of characteristic zero, $S$ in $\text{Def}_k$, and $Z$ in $\text{Def}_S$, a graded subgroup $I_SC(Z)$ of $C(Z)$ together with pushforward morphisms

$$f_i : I_SC(Z) \to I_SC(Y)$$

for every morphism $f : Z \to Y$ in $\text{Def}_S$. When $S$ is the final object $h[0, 0, 0]$ and $f$ is the morphism $Z \to S$, the morphism $f_i$ corresponds to motivic integration and we denote it by $\mu$.

Finally, fix $\Lambda$ in $\text{Def}_k$. Replacing dimension by relative dimension, we defined relative analogues $C(Z \to \Lambda)$ of $C(Z)$ for $Z \to \Lambda$ in $\text{Def}_\Lambda$ and extended the above constructions to this relative setting. In particular we constructed a morphism

$$\mu_\Lambda : I_\Lambda C(Z \to \Lambda) \to C(\Lambda) = I_\Lambda C(\Lambda \to \Lambda)$$

which corresponds to motivic integration along the fibers of the morphism $Z \to \Lambda$.

### 2.2. Cell decomposition.

We now recall the definition of cells given in [8], which is a slight generalization of the one in [29].

Let $C$ be a definable subassignment of $S$ where $S$ is in $\text{Def}_k$. Let $\alpha$, $\xi$, and $c$ be definable morphisms $\alpha : C \to \mathbb{Z}$, $\xi : C \to h_{\mathbf{G}_{m,k}}$, and $c : C \to h[1, 0, 0]$. The cell $Z_{C, \alpha, \xi, c}$ with basis $C$, order $\alpha$, center $c$, and angular component $\xi$ is the definable subassignment of $S[1, 0, 0]$ defined by $y$ in $C$, $\text{ord}(z - c(y)) = \alpha(y)$, and
$\overline{\mathcal{C}}(z - c(y)) = \xi(y)$, where $y$ lies in $S$ and $z$ in $h[1,0,0]$. Similarly, if $c$ is a definable morphism $c : C \to h[1,0,0]$, we define the cell $Z_{c,c}$ with center $c$ and basis $C$ as the definable subassignment of $S[1,0,0]$ defined by $y \in C$ and $z = c(y)$.

More generally, a definable subassignment $Z$ of $S[1,0,0]$ will be called a 1-cell, resp. a 0-cell, if there exists a definable isomorphism
\begin{equation}
\lambda : Z \to Z_C = Z_{C,a,\xi,c} \subset S[1,s,r],
\end{equation}
resp. a definable isomorphism
\begin{equation}
\lambda : Z \to Z_C = Z_{C,c} \subset S[1,s,0],
\end{equation}
for some $s,r \geq 0$ and some 1-cell $Z_{C,a,\xi,c}$, resp. 0-cell $Z_{C,c}$, such that the morphism $\pi \circ \lambda$, with $\pi$ the projection on the $S[1,0,0]$-factor, is the identity on $Z$.

We shall call the data $(\lambda, Z_{C,a,\xi,c})$, resp. $(\lambda, Z_{C,c})$, sometimes written for short $(\lambda, Z_C)$, a presentation of the cell $Z$.

One should note that $\lambda^*$ induces a canonical bijection between $C(Z_C)$ and $C(Z)$.

In [S], we proved the following variant of the Denef-Pas Cell Decomposition Theorem [29]:

2.2.1. Theorem. — Let $X$ be a definable subassignment of $S[1,0,0]$ with $S$ in $\text{Def}_k$.

1. The subassignment $X$ is a finite disjoint union of cells.
2. For every $\varphi$ in $C(X)$ there exists a finite partition of $X$ into cells $Z_i$ with presentation $(\lambda_i, Z_{C_i})$, such that $\varphi|_{Z_i} = \lambda_i^* p_{i*}(\psi_i)$, with $\psi_i$ in $C(C_i)$ and $p_i : Z_{C_i} \to C_i$ the projection. Similar statements hold for $\varphi$ in $C(X)$, in $P(X)$, and in $K_0(\text{RDef}_X)$.

We shall call a finite partition of $X$ into cells $Z_i$ as in Theorem 2.2.1 (1), resp. 2.2.1 (2) for a function $\varphi$, a cell decomposition of $X$, resp. a cell decomposition of $X$ adapted to $\varphi$.

The following result is already in [S] (Theorem 7.5.3), except for (6) that is new.

2.2.2. Theorem. — Let $X$ be in $\text{Def}_k$, $Z$ be a definable subassignment of $X[1,0,0]$, and let $f : Z \to h[1,0,0]$ be a definable morphism. There exists a cell decomposition of $Z$ into cells $Z_i$ such that the following conditions hold for every $\xi$ in $C_i$, for every $K$ in $\text{Field}_{k(\xi)}$, and for every 1-cell $Z_i$ with presentation $\lambda_i : Z_i \to Z_{C_i} = Z_{C_i,a,\xi,c_i}$ and with projections $p_i : Z_{C_i} \to C_i$, $\xi_i : Z_{C_i} \to h[1,0,0]$:

1. The set $\pi_i(p_i^{-1}(\xi))(K)$ is either empty or a ball of volume $L^{\alpha_i(\xi) - 1}$.
2. When $\pi_i(p_i^{-1}(\xi))(K)$ is nonempty, the function
\[
g_{\xi,K} : \begin{cases} 
\pi_i(p_i^{-1}(\xi))(K) \to K(\ell) \\
x \mapsto f \circ \lambda^{-1}(\xi,x)
\end{cases}
\]
is strictly analytic.

For each $i$ we can furthermore ensure that either $g_{\xi,K}$ is constant or (3) up to (6) hold.
(3) There exists a definable morphism $\beta_i : C_i \to h[0,0,1]$ such that

$$\text{ord } \frac{\partial}{\partial x} g_{\xi,K}(x) = \beta_i(\xi)$$

for every $x$ in $\pi_i(p_i^{-1}(\xi))(K)$.

(4) When $\pi_i(p_i^{-1}(\xi))(K)$ is nonempty, the map $g_{\xi,K}$ is a bijection onto a ball of volume $L^{-\alpha_i(\xi) - 1 - \beta_i(\xi)}$.

(5) For every $x,y$ in $\pi_i(p_i^{-1}(\xi))(K)$, $\text{ord}(g_{\xi,K}(x) - g_{\xi,K}(y)) = \beta_i(\xi) + \text{ord}(x-y)$.

(6) There exists a morphism $r_i : C_i \to h[1,0,0]$ such that for every $x$ in $\pi_i(p_i^{-1}(\xi))(K)$

$$g_{\xi,K}(x) = r_i(\xi) \text{ or } \text{ord}(g_{\xi,K}(x) - r_i(\xi)) \geq \alpha_i(\xi) + \beta_i(\xi).$$

Proof. — We only have to prove (6). First take a cell decomposition with properties (1) up to (5). By replacing $X$ we may suppose that the identity maps are presentations of the occurring cells. Then take a cell decomposition of $W \subset X[1,0,0]$, with $W = p(\text{graph } f)$ and $p : X[2,0,0] \to X[1,0,0]$ the projection on the $X$ and $f$ coordinates. The centers of the so obtained cells are approximations of $f$ as required in (6), and again by replacing $X$ one can assume that the identity maps are presentations of the occurring cells. Now take again a cell decomposition of $X$ such that properties (1) up to (5) are fulfilled. Then automatically (6) is fulfilled as well. □

3. Constructible exponential functions

3.1. Adding exponentials to Grothendieck rings. — Let $Z$ be in Def$_k$. We consider the category RDef$_Z^{\exp}$ whose objects are triples $(Y \to Z, \xi, g)$ with $Y$ in RDef$_Z$ and $\xi : Y \to h[0,1,0]$ and $g : Y \to h[1,0,0]$ morphisms in Def$_k$. A morphism $(Y' \to Z, \xi', g') \to (Y \to Z, \xi, g)$ in RDef$_Z^{\exp}$ is a morphism $h : Y' \to Y$ in Def$_Z$ such that $\xi' = \xi \circ h$ and $g' = g \circ h$. The functor sending $Y$ in RDef$_Z$ to $(Y,0,0)$, with 0 denoting the constant morphism with value 0 in $h[0,1,0]$, resp. $h[1,0,0]$ being fully faithful, we may consider RDef$_Z$ as a full subcategory of RDef$_Z^{\exp}$. We shall also consider the intermediate full subcategory RDef$_Z^e$ consisting of objects $(Y, \xi, 0)$ with $\xi : Y \to h[0,1,0]$ a morphism in Def$_k$.

To the category RDef$_Z^{\exp}$ one assigns a Grothendieck ring $K_0(\text{RDef}_Z^{\exp})$ defined as follows. As an abelian group it is the quotient of the free abelian group over symbols $[Y \to Z, \xi, g]$ with $(Y \to Z, \xi, g)$ in RDef$_Z^{\exp}$ by the following four relations

\begin{equation}
(3.1.1) \quad [Y \to Z, \xi, g] = [Y' \to Z, \xi', g']
\end{equation}

for $(Y \to Z, \xi, g)$ isomorphic to $(Y' \to Z, \xi', g')$,

\begin{equation}
(3.1.2) \quad [(Y \cup Y') \to Z, \xi, g] + [(Y \cap Y') \to Z, \xi_{|Y \cap Y'}, g_{|Y \cap Y'}] = [Y \to Z, \xi_{|Y'}, g_{|Y'}] + [Y' \to Z, \xi_{|Y'}, g_{|Y'}]
\end{equation}

for $Y$ and $Y'$ definable subassignments of some $X$ in RDef$_Z$ and $\xi$, $g$ defined on $Y \cup Y'$,

\begin{equation}
(3.1.3) \quad [Y \to Z, \xi, g + h] = [Y \to Z, \xi + \bar{h}, g]
\end{equation}
for $h : Y \to h[1, 0, 0]$ a definable morphism with $\text{ord}(h(y)) \geq 0$ for all $y$ in $Y$ and $\bar{h}$ the reduction of $h$ modulo $(t)$, and

$$Y[0, 1, 0] \to Z, \xi + p, g = 0$$

(3.1.4)

when $p : Y[0, 1, 0] \to h[0, 1, 0]$ is the projection and when $Y[0, 1, 0] \to Z, g$, and $\xi$ factorize through the projection $Y[0, 1, 0] \to Y$.

3.1.1. Lemma. — We may endow $K_0(\text{RDef}_{Z,\xi}^{\exp})$ with a ring structure by setting

$$[Y \to Z, \xi, g] \cdot [Y' \to Z, \xi', g'] = [Y \otimes_Z Y' \to Z, \xi \circ p_Y + \xi' \circ p_{Y'}, g \circ p_Y + g' \circ p_{Y'}],$$

where $Y \otimes_Z Y'$ is the fiber product of $Y$ and $Y'$, $p_Y$ the projection to $Y$, and $p_{Y'}$ the projection to $Y'$.

Proof. — Clearly fiber product induces a commutative ring structure on the free group on symbols $[Y \to Z, \xi, g]$ with $(Y \to Z, \xi, g)$ in $\text{RDef}_{Z,\xi}^{\exp}$. The subgroup generated by the four relations (3.1.1) up to (3.1.4) is an ideal of this ring, hence, the quotient by this subgroup is a ring.

Similarly, using relations (3.1.1), (3.1.2), (3.1.3), and the subcategory $\text{RDef}_{Z,\xi}^{\exp}$, one may define the subring $K_0(\text{RDef}_{Z,\xi}^{\exp})$ of $K_0(\text{RDef}_{Z}^{\exp})$.

3.1.2. Notation and abbreviations. — We write $e^\xi E(g)[Y \to Z]$ for $[Y \to Z, \xi, g]$. We abbreviate $e^0 E(g)[Y \to Z]$ by $E(g)[Y \to Z]$, $e^\xi E(0)[Y \to Z]$ by $e^\xi [Y \to Z]$, and $e^0 E(0)[Y \to Z]$ by $[Y \to Z]$. Likewise we write $e^\xi E(g)$ for $e^\xi E(g)[Z \to Z]$, $E(g)$ for $e^0 E(g)[Z \to Z]$ and $e^\xi$ for $e^\xi E(0)[Z \to Z]$. Note that the element $[Z \to Z]$ is the multiplicative unit of $K_0(\text{RDef}_{Z,\xi}^{\exp})$.

3.1.3. Lemma. — There are natural injections of rings $K_0(\text{RDef}_Z) \to K_0(\text{RDef}_{Z,\xi}^{\exp})$ sending $[Y \to Z]$ to $[Y \to Z]$ and $e^\xi[Y \to Z]$ to $e^\xi[Y \to Z]$.

Proof. — Both statements being similar, we prove that $i : K_0(\text{RDef}_Z) \to K_0(\text{RDef}_{Z,\xi}^{\exp})$ is an injection. Suppose that there are $a_1, a_2$ in $K_0(\text{RDef}_Z)$ having the same image in $K_0(\text{RDef}_{Z,\xi}^{\exp})$. The equality $i(a_1) = i(a_2)$ in $K_0(\text{RDef}_Z)$ induces an equality in the free group on symbols $[Y \to Z, \xi, 0]$ of the form

$$\sum_i [Y_i \to Z, \xi_i, 0] = \sum_j [Y_j \to Z, \xi_j, 0],$$

by adding up relations. For each $i, j$, let $Y'_i \subset Y_i$ and $Y'_j \subset Y_j$ be the subassignments defined by $\xi_i = 0$, resp. $\xi_j = 0$. Then

$$\sum_i [Y'_i \to Z, 0, 0] = \sum_j [Y'_j \to Z, 0, 0]$$

(3.1.6)

holds in the free group. Hence, $a_1 = a_2$ in $K_0(\text{RDef}_Z)$.
3.2. Pull-back. — For \( f : Z \rightarrow Z' \) in \( \text{Def}_k \) we have a natural pull-back morphism

\[ f^* : K_0(\text{RDef}_{Z'}^\exp) \rightarrow K_0(\text{RDef}_Z^\exp), \]

induced by fiber product.

If \( f : Z \rightarrow Z' \) is a morphism in \( \text{RDef}_Z \), composition with \( f \) induces a morphism

\[ f_! : K_0(\text{RDef}_{Z'}^\exp) \rightarrow K_0(\text{RDef}_Z^\exp). \]

We have similar morphisms when we replace \( \text{RDef}^\exp \) by \( \text{RDef}^e \).

3.3. Constructible exponential functions. — For \( Z \) in \( \text{Def}_k \) we define the ring \( C(Z)^\exp \) of constructible exponential functions by

\[ C(Z)^\exp := C(Z) \otimes_{K_0(\text{RDef}_Z)} K_0(\text{RDef}_Z^\exp). \]

Note that the element \( E(\text{id}) \) of \( C(h[1,0,0])^\exp \), with \( \text{id} \) the identity map on \( h[1,0,0] \), can be seen as a (non complex valued) additive character. Likewise, the element \( e^{\text{id}} \) of \( C(h[0,1,0])^\exp \), with \( \text{id} \) the identity map on \( h[0,1,0] \), can be seen as an additive character on the residue field.

For every \( d \geq 0 \) we define \( C^{\leq d}(Z)^\exp \) as the ideal of \( C(Z)^\exp \) generated by the characteristic functions \( 1_{Z'} \) of subassignments \( Z' \subset Z \) of dimension \( \leq d \).

We set

\[ C(Z)^\exp = \bigoplus_d C^d(Z)^\exp \]

with

\[ C^d(Z)^\exp := C^{\leq d}(Z)^\exp / C^{\leq d-1}(Z)^\exp. \]

It is a graded abelian group, and also a \( C(Z)^\exp \)-module. We call elements of \( C(Z)^\exp \) constructible exponential Functions.

For \( S \) in \( \text{Def}_k \) and \( Z \) in \( \text{Def}_S \) we define the group \( I_S C(Z)^\exp \) of \( S \)-integrable constructible exponential Functions by

\[ I_S C(Z)^\exp := I_S C(Z) \otimes_{K_0(\text{RDef}_Z)} K_0(\text{RDef}_Z^\exp). \]

It is a graded subgroup of \( C(Z)^\exp \).

3.3.1. Lemma. — For every \( Z \) in \( \text{Def}_k \), the natural morphisms of rings, resp. of graded groups, \( C(Z) \rightarrow C(Z)^\exp \), \( C^{\leq d}(Z) \rightarrow C^{\leq d}(Z)^\exp \), resp. \( C(Z) \rightarrow C(Z)^\exp \), \( I_S C(Z) \rightarrow I_S C(Z)^\exp \) are injective.

Proof. — This follows from Lemma 3.1.3 by taking tensor products, and by noting that \( C^{\leq d}(Z)^\exp \) is isomorphic to \( C^{\leq d}(Z) \otimes_{K_0(\text{RDef}_Z)} K_0(\text{RDef}_Z^\exp) \).

3.3.2. Proposition. — Let \( S \) be in \( \text{Def}_k \) and let \( W \) be a definable subassignment of \( h[0,0,m] \). The canonical morphism

\[ K_0(\text{RDef}_S^\exp) \otimes_{\mathcal{P}_0(S)} \mathcal{P}^0(S \times W) \rightarrow K_0(\text{RDef}_{S \times W}^\exp) \]

is an isomorphism.

Proof. — This follows from the Denef-Pas quantifier elimination as stated in [8].
3.4. Inverse image of constructible exponential functions. — Let \( f : Z \to Z' \) be a morphism in \( \text{Def}_k \). Since \( f^* \) as defined on \( K_0(\text{RDef}^{\exp}_Z) \) and on \( C(Z') \) is compatible with the morphisms \( K_0(\text{RDef}_Z) \to C(Z') \) and \( K_0(\text{RDef}_Z) \to K_0(\text{RDef}^{\exp}_Z) \), one gets by tensor product a natural pull-back morphism \( f^* : C(Z')^{\exp} \to C(Z)^{\exp} \).

3.5. Push-forward for inclusions. — Let \( i : Z \hookrightarrow Z' \) be the inclusion between two definable subassignments \( Z \subset Z' \). Extension by zero induces a morphism \( i^* : K_0(\text{RDef}^{\exp}_Z) \to K_0(\text{RDef}^{\exp}_Z) \). Since this is compatible on \( K_0(\text{RDef}_Z) \) with \( i^* : C(Z) \to C(Z') \), we get, by tensor product, a morphism \( i^* : C(Z)^{\exp} \to C(Z')^{\exp} \). Because \( i \) sends subassignments of \( Z \) to subassignments of \( Z' \) of the same dimension, there are group morphisms \( i^* : C^{\leq d}(Z)^{\exp} \to C^{\leq d}(Z')^{\exp} \), and graded group morphisms \( i^* : C(Z)^{\exp} \to C(Z')^{\exp} \). If \( Z' \) is in \( \text{Def}_S \) then \( i^* \) clearly restricts to a morphism \( f_i : I_\delta C(Z)^{\exp} \to I_\delta C(Z')^{\exp} \).

3.6. Push-forward for \( k \)-projections. — Let \( Y \) be in \( \text{Def}_k \) and let \( Z \) be a definable subassignment of \( Y'_{[0,r,0]} \), for some \( r \geq 0 \). Denote by \( f : Z \to Y \) the morphism induced by projection. It follows from statement (1) in Proposition 5.2.1 of [8] that the map \( f_! : K_0(\text{RDef}^{\exp}_Z) \to K_0(\text{RDef}^{\exp}_Y) \) induces a ring morphism \( f_! : C(Z)^{\exp} \to C(Y)^{\exp} \), and because \( f \) sends subassignments of \( Z \) to subassignments of \( Y \) of the same dimension, there are group morphisms \( f_! : C^{\leq d}(Z)^{\exp} \to C^{\leq d}(Y)^{\exp} \), and graded group morphisms \( f_! : C(Z)^{\exp} \to C(Y)^{\exp} \). If \( Y \) is in \( \text{Def}_S \) then \( f_! \) clearly restricts to a morphism \( f_! : I_\delta C(Z)^{\exp} \to I_\delta C(Y)^{\exp} \). Note also that the projection formula trivially holds in this setting, that is, for every \( \alpha \) in \( C(Y)^{\exp} \) and \( \beta \) in \( C(Z)^{\exp} \), \( f_!(f^*(\alpha) \beta) = \alpha f_!(\beta) \).

3.7. Push-forward for \( Z \)-projections. — If \( f : Z_{[0,0,m]} \to Z \) is the projection and \( Z \) is in \( \text{Def}_S \), \( m \geq 0 \), then, by Proposition 3.5.2 and by the fact that \( f \) preserves the dimension of definable subassignments of \( Z_{[0,0,m]} \), the map \( f_! : I_\delta C(Z_{[0,0,m]}) \to I_\delta C(Z) \) induces a graded group morphism \( f_! : I_\delta C(Z_{[0,0,m]})^{\exp} \to I_\delta C(Z)^{\exp} \).

Lemma-Definition 3.7.1 below is a basic kind of Fubini Theorem between the push forwards of 3.6 and 3.7 and Lemma 3.7.2 is a basic form of the change of variables formula.

3.7.1. Lemma-Definition. — Let \( \varphi \) be in \( I_\delta C(Z_{[0,m,r]})^{\exp} \) for some \( m, r \geq 0 \) and some \( Z \) in \( \text{Def}_S \) and let \( f : Z_{[0,m,r]} \to Z \) the projection. Let \( \pi_1, \ldots, \pi_{m+r} \) be any sequence of linear projections of the form \( Z_{[0,i,j]} \to Z_{[0,i-1,j]} \) or \( Z_{[0,i,j]} \to Z_{[0,i,j-1]} \) whose composition goes from \( Z_{[0,m,r]} \) to \( Z \). Then, \( \pi_{m+r} \circ \ldots \circ \pi_1(\varphi) \) is independent of the sequence \( \pi_1, \ldots, \pi_{m+r} \) and we define \( f_!(\varphi) \) to be this element.

Proof. — This follows from the fact that
\[
K_0(\text{RDef}^{\exp}_{Z_{[0,m,0]}}) \otimes_{K_0(\text{RDef}^{\exp}_Z)} C(Z)^{\exp} \otimes_{C(Z)} C(Z_{[0,0,r]}) \to C(Z_{[0,m,r]})^{\exp}
\]
is an isomorphism. □
Let $\lambda : S[0, n, r] \to S[0, n', r']$ be a morphism in $\text{Def}_S$. Let $\varphi$ be a function in $C(S[0, n, r])^{\exp}$. Assume $\varphi = 1_Z \varphi$ with $Z$ a definable subassignment of $S[0, n, r]$ on which $\lambda$ is injective. Thus $\lambda$ restricts to an isomorphism $\lambda'$ between $Z$ and $Z' := \lambda(Z)$. We define $\lambda_+(\varphi)$ in $C(S[0, n', r'])^{\exp}$ as $[i'_!(\lambda^{-1})^*i^*(\varphi)]$, where $i$ and $i'$ denote respectively the inclusions of $Z$ and $Z'$ in $S[0, n, r]$ and $S[0, n', r']$.

### Lemma 3.7.2

Let $\lambda : S[0, n, r] \to S[0, n', r']$ be a morphism in $\text{Def}_S$. Let $\varphi$ be a function in $C(S[0, n, r])^{\exp}$ such that $\varphi = 1_Z \varphi$ with $Z$ a definable subassignment of $S[0, n, r]$ on which $\lambda$ is injective. Then $\varphi$ is in $I_S C(S[0, n, r])^{\exp}$ if and only if $\lambda_+(\varphi)$ is in $I_S C(S[0, n', r'])^{\exp}$ and if this is the case then

$$p_t(\varphi) = p'_t(\lambda_+(\varphi)), \quad \text{with } p : S[0, n, r] \to S \text{ and } p' : S[0, n', r'] \to S \text{ the projections and } p_t \text{ and } p'_t \text{ as in Lemma-Definition 3.7.1}.$$

**Proof.** Consider the definable isomorphism

$$\lambda \times \text{id} : S[0, n, r] \to S[0, n + n', r + r']$$

with inverse $g$. Since this is an isomorphism, $\varphi$ is $S$-integrable if and only if $g^*(\varphi)$ is $S$-integrable. By construction,

$$\pi'_t(g^*(\varphi)) = \lambda_+(\varphi),$$

$$\pi_t(g^*(\varphi)) = \varphi,$$

with $\pi : S[0, n + n', r + r'] \to S[0, n, r]$ and $\pi' : S[0, n + n', r + r'] \to S[0, n', r']$ the projections. Now the Lemma follows from Lemma-Definition 3.7.1. □

### 3.8. Relative setting

Let us fix $\Lambda$ in $\text{Def}_\Lambda$ that will play the role of a parameter space. For $Z$ in $\text{Def}_\Lambda$, we consider, similarly as in [8], the ideal $C^{\leq d}(Z \to \Lambda)^{\exp}$ of $C(Z)^{\exp}$ generated by functions $1_{Z'}$ with $Z'$ definable subassignment of $Z$ such that all fibers of $Z' \to \Lambda$ have dimension $\leq d$. We set

$$C(Z \to \Lambda)^{\exp} := \bigoplus_d C^d(Z \to \Lambda)^{\exp}$$

with

$$C^d(Z \to \Lambda) := C^{\leq d}(Z \to \Lambda)/C^{\leq d-1}(Z \to \Lambda).$$

This graded abelian semigroup may be naturally identified with

$$C(Z \to \Lambda) \otimes_{K_0(\text{RDef}_Z)} K_0(\text{RDef}_Z^{\exp}).$$

For $Z \to S$ a morphism in $\text{Def}_\Lambda$, we set

$$I_S C(Z \to \Lambda)^{\exp} := I_S C(Z \to \Lambda) \otimes_{K_0(\text{RDef}_Z)} K_0(\text{RDef}_Z^{\exp}).$$

Lemma 3.3.1 and all results and constructions in [3.5], [3.6], [3.7], including Lemma-Definition 3.7.1 and Lemma 3.7.2 extend immediately with the same proofs to the relative setting.
4. Integration of constructible exponential functions

4.1. The main result. — We can now state the result on extending our construction of motivic integrals from constructible functions to constructible exponential functions.

4.1.1. Theorem. — Let $S$ be in $\text{Def}_k$. There is a unique functor from the category $\text{Def}_S$ to the category of abelian groups which sends $Z$ to $I_S C(Z)^{\exp}$, assigns to every morphism $f : Z \to Y$ in $\text{Def}_S$ a morphism $f_i : I_S C(Z)^{\exp} \to I_S C(Y)^{\exp}$ and which satisfies the following five axioms:

(A1) Compatibility: For every morphism $f : Z \to Y$ in $\text{Def}_S$, the map $f_i : I_S C(Z)^{\exp} \to I_S C(Y)^{\exp}$ is compatible with the inclusions of groups $I_S C(Z) \to I_S C(Z)^{\exp}$ and $I_S C(Y) \to I_S C(Y)^{\exp}$ and with the map $f : I_S C(Z) \to I_S C(Y)$ as constructed in [8].

(A2) Disjoint union: Let $Z$ and $Y$ be definable subassignments in $\text{Def}_S$. Assume $Z$, resp. $Y$, is the disjoint union of two definable subassignments $Z_1$ and $Z_2$, resp. $Y_1$ and $Y_2$ of $Z$, resp. $Y$. Then, for every morphism $f : Z \to Y$ in $\text{Def}_S$, with $f(Z_i) \subset Y_i$ for $i = 1, 2$, under the isomorphisms $I_S C(Z)^{\exp} \simeq I_S C(Z_1)^{\exp} \oplus I_S C(Z_2)^{\exp}$ and $I_S C(Y)^{\exp} \simeq I_S C(Y_1)^{\exp} \oplus I_S C(Y_2)^{\exp}$, we have $f_i = f_{1i} + f_{2i}$, with $f_i : Z_i \to Y_i$ the restrictions of $f$.

(A3) Projection formula: For every morphism $f : Z \to Y$ in $\text{Def}_S$, and every $\alpha$ in $C(Y)^{\exp}$ and $\beta$ in $I_S C(Z)^{\exp}$, if $f^*(\alpha) \beta$ is in $I_S C(Z)^{\exp}$, then $f_i(f^*(\alpha) \beta) = \alpha f_i(\beta)$.

(A4) Projection on $k$-variables: Assume that $f$ is the projection $f : Z = Y[0, n, 0] \to Y$ for some $Y$ in $\text{Def}_S$. For every $\varphi$ in $I_S C(Z)^{\exp}$, $f_i(\varphi)$ is as constructed in [3, 4].

(A5) Relative balls of large volume: Let $Y$ be in $\text{Def}_S$ and consider definable morphisms $\alpha : Y \to Z$, $\xi : Y \to h_{G_{m,k}}$, with $G_{m,k}$ the multiplicative group $A^1_k \setminus \{0\}$. Suppose that $[1_Z]$ is in $I_S C(Z)^{\exp}$ and that $Z$ is the definable subassignment of $Y[1, 0, 0]$ defined by $\text{ord } z = \alpha(y)$ and $\text{ord } z = \xi(y)$, and $f : Z \to Y$ is the morphism induced by the projection $Y[1, 0, 0] \to Y$. If moreover $\alpha(y) < 0$ holds for every $y$ in $Y$, then

$$f_i(E(z)[1_Z]) = 0.$$ 

Moreover, these groups morphisms $f_i$ coincide with the group morphisms constructed in [3, 4] and in [5, 6] in the corresponding cases.

When $S = h[0, 0, 0]$, we write $I C(Y)^{\exp}$ for $I_S C(Y)^{\exp}$ and $\mu$ for the morphism $f_i : I C(Y)^{\exp} \to I C(h[0, 0, 0])^{\exp} = K_0(\text{RDef}_{h[0, 0, 0]}^{\exp}) \otimes_{\mathbb{Z}[L]} A$ when $f : Y \to h[0, 0, 0]$ is the projection to the final object.
4.2. Change of variables formula. — We have the following analogue of Theorem 12.1.1 of \([8]\).

4.2.1. Theorem (Change of variables formula). — Let \(f : X \to Y\) be a definable isomorphism between definable subassignments of dimension \(d\). Let \(\varphi\) be in \(C^{\leq d}(Y)^\exp\) with a non zero class in \(C^d(Y)^\exp\). Then \([f^*(\varphi)]\) belongs to \(I_YC^d(X)^\exp\) and

\[
f_!([f^*(\varphi)]) = L_{\operatorname{ordjac}f^{-1}}[\varphi].
\]

Proof. — Similar to the proof of Theorem 12.1.1 of \([8]\). It is enough to consider the cases where \(f\) is an injection or a projection. When \(f\) is an injection the statement is true by construction. For projections, one reduces to the case of the projection of a 0-cell as in Proposition 11.4.3 of \([8]\), which follows also by construction.

4.3. Relative version. — Fix \(\Lambda\) in \(\text{Def}_{k}\). The proof of Theorem 4.1.1 which we shall give in sections 5 and 6 readily extends to the following relative version:

4.3.1. Theorem. — Let \(\Lambda\) belong to \(\text{Def}_{k}\) and let \(S\) belong to \(\text{Def}_{\Lambda}\). There exists a unique functor from \(\text{Def}_S\) to the category of abelian groups assigning to any morphism \(f : Z \to Y\) in \(\text{Def}_S\) a morphism

\[
f_{\Lambda} : I_S C(Z \to \Lambda)^\exp \to I_S C(Y \to \Lambda)^\exp
\]

satisfying the analogues of axioms (A1)-(A5) when replacing \(C(\_\_)\) by \(C(\_\_ \to \Lambda)\).

Let \(Z\) be in \(\text{Def}_{\Lambda}\). For every point \(\lambda\) of \(\Lambda\), we denote by \(Z_{\lambda}\) the fiber of \(Z\) at \(\lambda\), as defined in \([8]\) 2.6. We have a natural restriction morphism \(i_{\lambda}^* : C(Z \to \Lambda)^\exp \to C(Z_{\lambda})^\exp\), which respects the grading. Let \(f : Z \to Y\) be a morphism in \(\text{Def}_{\Lambda}\) and let \(\varphi\) be in \(C(Z \to \Lambda)^\exp\). We denote by \(f_{\lambda} : Z_{\lambda} \to Y_{\lambda}\) the restriction of \(f\) to the fiber \(Z_{\lambda}\). It follows from Proposition 14.2.1 of \([8]\) that if \(\varphi\) is in \(I_Y C(Z \to \Lambda)^\exp\), then \(i_{\lambda}^*(\varphi)\) is in \(I_{Y_{\lambda}} C(Z_{\lambda})^\exp\). Furthermore, it follows from the constructions that, then

\[
i_{\lambda}^*(f_{\lambda}(\varphi)) = f_{\lambda}i_{\lambda}^*(\varphi)
\]

for every point \(\lambda\) of \(\Lambda\).

When \(S = \Lambda\) and \(f\) is the morphism \(Z \to \Lambda\), we write \(\mu_{\Lambda}\) for the morphism \(f_{\Lambda} : I_{\Lambda} C(Z \to \Lambda)^\exp \to C(\Lambda)^\exp = I_{\Lambda} C(\Lambda \to \Lambda)^\exp\).

4.3.2. Remark. — It follows from the functoriality statement in Theorem 4.1.1 and Proposition 14.2.1 that for \(f : X \to Y\) and \(g : Y \to Z\) in \(\text{Def}_S\), \((g \circ f)_! = g_! \circ f_!\), resp. \((g \circ f)^! = g^! \circ f^!\). We shall sometimes refer to that property as “Fubini Theorem”.

4.4. Global version. — Once we have Theorem 4.2.1 at our disposal it is possible to develop the theory on global subassignments, defined by replacing affine spaces by general algebraic varieties, along the lines of section 15 of \([8]\). Since this is essentially straightforward we shall not give more details here.
5. Exponential integrals in dimension 1

We shall start by constructing directly exponential integrals in relative valued field dimension 1.

5.1. — Let \( S \) be a definable subassignment and consider a definable subassignment \( X \subset S[1,0,0] \) and denote by \( \pi : X \to S \) the projection. Let \( M_X \) be the free group on symbols \([Y \to X, \xi, g, \varphi]\) with \((Y \to X, \xi, g, \varphi) \) in \( \text{RDef}^\exp_X \times I_S C(X) \).

We construct a map

\[
\pi_1 : M_X \to C(S)^{\exp}
\]

and show that it factorizes through the natural surjective group morphism \( M_X \to I_S C(X)^{\exp} \), thus obtaining a map

\[
\pi_1 : I_S C(X)^{\exp} \to C(S)^{\exp},
\]

which is the integral in relative dimension 1.

Consider \( a = [f : Y \to X, \xi, g, \varphi] \) in \( M_X \).

We shall use a suitable isomorphism of the form \( \lambda : Y \to Y' \subset Y[0,n,r] \) which is an isomorphism over \( Y \) and which is adapted to \( a \) in a certain sense. Then we shall define \( \pi_1 \) by going through the commutative diagram

\[
\begin{array}{ccc}
Y & \xrightarrow{f} & X \\
\downarrow{\lambda} & & \downarrow{\pi} \\
Y' & \xrightarrow{\pi_1} & S' := S[0,n+n_Y, r] \\
& & \xrightarrow{p}
\end{array}
\]

where \( Y \subset X[0,n_Y, 0] \), \( \pi' \) and \( p \) are the projections, and where we will write \( Y' \) as the disjoint union of \( A_1, A_2, \) and \( B \), along which \( \pi_1' \) will be easy to define.

Let \( a' \) be \([Y' \to Y', \xi' := \xi \circ \lambda^{-1}, g' := g \circ \lambda^{-1}, \varphi' := \lambda^{-1} f^*(\varphi)] \) in \( M_{Y'} \). We construct \( \lambda \), define \( \pi_1'(a') \), and then define \( \pi_1(a) \) as \( p \pi_1'(a') \), where \( p \) is as in Lemma-Definition 3.7.1

Write \( \varphi' \) as \( \sum_{i=1}^{2} [\varphi_i'] \) with \( \varphi_i' \) in \( C^{\leq i}(Y) \) but not in \( C^{\leq i-1}(Y) \setminus \{0\} \). By Theorems 2.2.1 and 2.2.2 we can take an appropriate \( \lambda \) such that \( \xi' = \xi \circ \pi' \) for some \( \xi : S' \to h[0,1,0] \), such that \( \varphi_i' = \pi'^*(\varphi_i) \) for some \( \varphi_i \in C(S') \), and such that properties (1) up to (6) of Theorem 2.2.2 are fulfilled for \( g' \). There are now uniquely determined parts \( A, B \subset Y' \), such that \( g'(x,\cdot) : y \mapsto g'(x, y) \) is constant on \( B_x \) for each \( x \), and nonconstant and injective on \( A_x \) for each \( x \), where \( A_x = \{y \in h[1,0,0] | (x,y) \in A\} \) and \( B_x = \{y \in h[1,0,0] | (x,y) \in B\} \) are the fibers, and \( x \) runs over \( S' \).

It is clear that \( g'_{|B} = \tilde{g} \circ \pi'_{|B} \) for a unique definable \( \tilde{g} : \pi'(B) \to h[1,0,0] \).

On the part \( A \) we have to work differently. By construction, \( A \) is a 1-cell having the identity morphism as presentation. By the previous use of Theorem 2.2.2, \( A \) is
the disjoint union of $A_1$ and $A_2$, with

$$(5.1.3) \quad A_1 := \{ (x, y) \in A \mid g'(x, \cdot) \text{ maps } A_x \text{ onto a ball of volume } L^j \text{ with } j \leq 0 \}. $$

$$(5.1.4) \quad A_2 := \{ (x, y) \in A \mid g'(x, \cdot) \text{ maps } A_x \text{ onto a ball of volume } L^j \text{ with } j > 0 \}. $$

Note that the $A_i$ are cells which are their own presentation.

By property (6) of Theorem $2.2.2$, there are definable morphisms $r : S' \to h[1, 0, 0]$ and $\eta : S' \to h[0, 1, 0]$ such that

$$(5.1.5) \quad g'(x, y) - r(x) \equiv \eta(x) \pmod{(t)}$$

for $(x, y) \in A_2$, that is, either $r_i(x) - g'(x, y)$ has order $> 0$ and $\eta(x) = 0$, or, it has order $0$ and angular component equal to $\eta(x)$.

#### 5.1.1. Lemma-Definition.

Consider $\lambda$, $A_1$, $A_2$, $B$, $r$, and $\eta$ as constructed above. Define $\pi_i'(a')$ in $C(S')^{\exp}$ as

$$\pi_i'(a') := e^g E(\tilde{g}) \pi_i'(1_B \varphi') + e^g \eta E(r(\tilde{g})) \pi_i'(1_{A_2} \varphi')$$

where $\pi_i'$ in the right hand side is as in [8]. Then, $\pi_i'(a')$ lies in $I_S C(S')^{\exp}$ and is independent of the choice of $r$ and $\eta$. Furthermore, $p_i(\pi_i'(a'))$, where $p_i$ is as in Lemma-Definition $3.7.1$, is independent of the choice of $\lambda$, so we can define $\pi_i(a)$ in $C(S)^{\exp}$ as

$$\pi_i(a) := p_i(\pi_i'(a')).$$

We extend $\pi_i$ to a group morphism $\pi_i : M_X \to C(S)^{\exp}$.

**Proof.** — That $\pi_i'(\varphi')$ lies in $I_S C(S')^{\exp}$ follows easily from the fact that $\pi_i'(1_B \varphi')$ and $\pi_i'(1_{A_1} \varphi')$ are in $I_S C(S')$, which is true by the main theorem of [8] and the fact that $\varphi$ is in $I_S C(X)$. The independence from the choice of $r$ and $\eta$ is clear by relation (3.1.3) for $C(S)^{\exp}$.

We prove the independence from the choice of $\lambda : Y \to Y'$. Although this is similar to the proof of Lemma-Definition 9.1.2 in [8], using furthermore relation (3.1.4), let us give details. If another map $\tilde{\lambda} : Y \to Y'$ with the same properties and with partition $\tilde{A}_1, \tilde{A}_2, \tilde{B}$ is given, there exists a third map $\hat{\lambda} : Y \to \hat{Y}$ with the same properties and with partition $\hat{A}_1, \hat{A}_2, \hat{B}$, such that $\hat{\lambda}^{-1}(\tilde{B})$ contains both $\tilde{\lambda}^{-1}(\hat{B})$ and $\lambda^{-1}(B)$, for example, the map $\hat{\lambda} := \lambda \otimes_Y \tilde{\lambda}$ has this property. Necessarily, $\hat{\lambda}^{-1}(\hat{B})$ is equal to the union of $\lambda^{-1}(B)$ with a 0-cell and is also equal to the union of $\tilde{\lambda}^{-1}(\tilde{B})$ with a 0-cell, since $g'$ is injective on $A$. It follows from this, from $\varphi_i = \pi_i^* (\varphi_i)$ and since $A$ is a 1-cell, that one has

$$(5.1.6) \quad p_i \pi_i'(1_B \varphi') = \tilde{p}_i \tilde{\pi}_i'(1_B \varphi') = \hat{p}_i \hat{\pi}_i'(1_B \varphi'),$$

with obvious notation (this also follows from Lemma-Definition 9.1.2 in [8]). By Lemma-Definition 3.7.1 one finds

$$(5.1.7) \quad p_i(e^g E(\tilde{g}) \pi_i'(1_B \varphi')) = \tilde{p}_i(e^{g} E(\tilde{g}) \tilde{\pi}_i'(1_B \varphi')) = \hat{p}_i(e^{g} E(\tilde{g}) \hat{\pi}_i'(1_B \varphi')).$$
Next we compare the integrals over $A$, $\hat{A}$ and $\check{A}$, working still similarly as in the proof of Lemma-Definition 9.1.2 in [8].

Note that automatically we have the following inclusions

\[(5.1.8)\quad \check{\lambda}^{-1}(\check{A}) \subset \lambda^{-1}(A), \quad \hat{\lambda}^{-1}(\hat{A}) \subset \hat{\lambda}^{-1}(\check{A}),\]

\[(5.1.9)\quad \check{\lambda}^{-1}(\check{A}_1) \subset \lambda^{-1}(A_1), \quad \hat{\lambda}^{-1}(\hat{A}_1) \subset \hat{\lambda}^{-1}(\check{A}_1),\]

but maybe not so for $A_2$. By Lemma-Definition 9.1.2 in [8], one has

\[(5.1.10)\quad p_!\pi_!'(1_A\varphi') = \check{p}_!\check{\pi}_!'(1_{\check{A}}\check{\varphi}') = \hat{p}_!\hat{\pi}_!'(1_{\hat{A}}\hat{\varphi}').\]

The subassignment $\check{\lambda}^{-1}(\check{A}_2)$ is equal to $\lambda^{-1}(A_2)$ with a 1-cell $C$ adjoined and with a 0-cell removed. In our construction, since $\varphi'_i = \pi''(\varphi_i)$, the pushforward is stable under removing a 0-cell from $A$ (or from $A_2$). Relation (3.1.4) insures that the integral over $C$ is equal to zero, hence, the lemma is proved. \qed

5.1.2. Lemma-Definition. — The map $\pi_1$ constructed in Lemma-Definition 6.1.1 factorizes through the natural group homomorphism $M_X \to I_S C(X)^{\exp}$. We write $\pi_1$ for the induced group homomorphism

\[\pi_1 : I_S C(X)^{\exp} \to C(S)^{\exp}.\]

Proof. — We have to check that $\pi_1 : M_X \to C(S)^{\exp}$ factorizes through the tensor product $N_X \otimes_{K_0(\text{RDef}_X)} I_S C(X)$, with $N_X$ the free group on symbols $[b]$ with $b$ in $\text{RDef}_X^{\exp}$, and then we have to check that it factorizes through the relations (3.1.1) up to (3.1.3). By construction, $\pi_1 : M_X \to C(S)^{\exp}$ is bilinear in the factors $N_X$ and $I_S C(X)$ over the ring $K_0(\text{RDef}_X)$, hence it factorizes through $N_X \otimes_{K_0(\text{RDef}_X)} I_S C(X)$.

That $\pi_1$ factors through relation (3.1.1) is clear since its definition is independent of the choice of $\lambda$, cf. Lemma-Definition 5.1.1. Relation (3.1.2) is clear by construction. Relation (3.1.3) also follows since we can choose $\lambda$ in such a way that $\hat{h}$ factors through the projection $\pi'$, and then one can compare the original construction and definition with the ones with $g$ replaced by $g + h$. We prove relation (3.1.4). Assume that $a$ is of the form $[Y[0,1,0] \to X, \xi + p, g, \varphi]$ with $p : Y[0,1,0] \to h[0,1,0]$ the projection and that $Y[0,1,0] \to X, g$, and $\xi$ factorize through the projection $Y[0,1,0] \to Y$. It follows by construction from relation (3.1.4) that $\pi_1(a)$ is zero. \qed

One deduces from Theorem 2.2.2 the following change of variables statement in relative dimension 1:

5.1.3. Proposition (Change of variables). — Let $X$ and $Y$ be definable subassignments of dimension $r$ of $S[1,0,0]$ for some $S$ in $\text{Def}_k$ and let $f : X \to Y$ be a definable isomorphism over $S$. Suppose that $X$ and $Y$ are equidimensional of relative dimension 1 relative to the projection to $S$. Then, $\varphi$ is in $I_S C^n(Y)^{\exp}$ if and only if $L^{\text{ordjac}} f^*(\varphi)$ is in $I_S C^n(X)^{\exp}$ and if this is the case then

\[\pi_{Y!}(\varphi) = \pi_{X!}(L^{\text{ordjac}} f^*(\varphi))\]
holds in $C(S)^{\exp}$ with $\pi_Y : Y \rightarrow S$ and $\pi_X : X \rightarrow S$ the projections, $\pi_{Y^!}, \pi_{X^!}$ as in Lemma-Definition 5.1.2 and ordjac as in \cite{8}.

Proof. — By linearity we may assume that $\varphi$ is of the form
\begin{equation}
\varphi = e^g E(g)(Z \rightarrow Y)\varphi_0,
\end{equation}
with $\varphi_0$ in $I_S C(Y)$, $Z \subset Y[0,n,0]$, and $\xi : Z \rightarrow h[0,1,0]$ and $g : Z \rightarrow h[1,0,0]$ definable morphisms. By pulling back along $Z \rightarrow Y$, we may assume that $Z = Y$. Choose $\lambda$ as in the construction of $\pi_{Y^!}(\varphi)$ in Lemma-Definition 5.1.2. By changing $\lambda$ we may suppose that Theorem 2.2.2 is also applied to the function $p_1 \circ f$, with $p_1 : X \rightarrow h[1,0,0]$ the projection. But then $\lambda \circ f$ can be used to compute $\pi_{X^!}(L^{\text{ordjac}} f^*(\varphi))$ as in Lemma-Definition 5.1.2 and is seen to be equal to $\pi_{Y^!}(\varphi)$.

6. Proof of Theorem 4.1.1

6.1. Notation. — If $p : X \rightarrow Z$ is a morphism in $\text{RDef}_Z$ and $\varphi$ a function in $C^h(Z)$ which is the class of $\psi$ in $C^e(Z)$, the class of $p^*(\psi)$ in $C^h(X)$ depends only of $\varphi$, so we denote it by $p^*(\varphi)$. This construction extends by linearity to a morphism $p^* : C(Z) \rightarrow C(X)$.

6.2. — Replacing $K_0(\text{RDef}_Z^{\exp})$ by the subring $K_0(\text{RDef}_Z^e)$, one defines subobjects $C(Z)^e$, $C(Z)^e$ and $I_S C(Z)^e$ of $C(Z)^{\exp}$, $C(Z)^{\exp}$ and $I_S C(Z)^{\exp}$ defined in \cite{8} cf. Lemma 3.1.3.

Let us first prove that Theorem 4.1.1 restricted to this setting hold:

6.2.1. Proposition. — Let $S$ be in $\text{Def}_L$. There is a unique functor from the category $\text{Def}_S$ to the category of abelian groups which sends $Z$ to $I_S C(Z)^e$, assigns to every morphism $f : Z \rightarrow Y$ in $\text{Def}_S$ a morphism $f_1 : I_S C(Z)^e \rightarrow I_S C(Y)^e$ and which satisfies axioms (A1) to (A4) of Theorem 4.1.1. Moreover, these groups morphisms $f_1$ coincide with the group morphisms constructed in 3.7 and in 3.8 in the corresponding cases.

Proof. — Let $f : Z \rightarrow Y$ be a morphism in $\text{Def}_S$. Consider $\varphi$ in $I_S C(Z)^e$ of the form
\begin{equation}
e^h[X \rightarrow Z] \varphi_0
\end{equation}
with $p : X \rightarrow Z$ in $\text{RDef}_Z$, $h : X \rightarrow h[0,1,0]$ and $\varphi_0$ in $I_S C(Z)$. We have
\begin{equation}
\varphi = p_1(e^h p^* \varphi_0).
\end{equation}
Hence, if we denote by $\delta_{f,h} : X \rightarrow Y[0,1,0]$ the morphism
\begin{equation}
x \mapsto ((f \circ p)(x), h(x)),
\end{equation}
the axioms force to set
\begin{equation}
f_1(\varphi) := \pi_{Y^!}(e^h \delta_{f,h}(p^* \varphi_0)),
\end{equation}
with \( \pi_Y \) the projection \( Y[0, 1, 0] \to Y \), \( \xi \) the canonical coordinate on the fibers of \( \pi \), and \( \pi_{Y!} \) uniquely determined by (A4). Since \( I_S C(Z)^\circ \) is generated by functions \( \varphi \) as above, this proves the unicity part of the statement. For existence, one uses (6.2.4) to define \( p_! \) by additivity. Note that this definition is clearly compatible with the relations involved in the definition of \( C(Z)^\circ \). Note also that (A2) and (A1) are obvious and that (A4), that is, compatibility with \( \delta_{g, \xi_0} \) is easily checked. The projection formula (A3) follows easily from the projection formula in \( \mathbb{F} \).

Now let us prove functoriality, namely, that \( g_t \circ f_t = (g \circ f)_t \) for morphisms \( f : Z \to Y \) and \( g : Y \to W \) in \( \text{Def}_S \). As above consider \( \varphi \) in \( I_S C(Z)^\circ \) of the form \( e^h[X \to Z] \varphi_0 = p!(e^h p^* \varphi_0) \) with \( p : X \to Z \) in \( \text{RDef}_Z \), \( h : X \to h[0, 1, 0] \) and \( \varphi_0 \) in \( I_S C(Z) \). We have

\[
(6.2.5) \quad (g_t \circ f_t)(\varphi) = g_t(\pi_{Y!}((e^h \delta_{f, h!}(p^* \varphi_0)))
\]

and

\[
(6.2.6) \quad (g \circ f)_t(\varphi) = \pi_{Y!}(e^h \delta_{p, f, h!}(p^* \varphi_0))
= \pi_{Y!}(e^h((g \times \text{id})_t \circ \delta_{f, h!})(p^* \varphi_0)),
\]

hence it is enough to check that for every \( \psi \) in \( I_S C(Y[0, 1, 0]) \)

\[
(6.2.7) \quad g_t(\pi_{Y!}(e^h \psi)) = \pi_{Y!}(e^h((g \times \text{id})_t \psi)).
\]

We may assume \( \psi \) is of the form \([p : X \to Y[0, 1, 0]] \pi_Y^*(\psi_0)\) with \( \psi_0 \) in \( I_S C(Y) \)
the class of a function in some \( C^i(Y) \), and with the above abuse of notation. Since
\( \pi_{Y!}(e^h \psi) = e^{h_{\text{op}}}[X \to Y] \psi_0 \) we have

\[
(6.2.8) \quad g_t(\pi_{Y!}(e^h \psi)) = \pi_{Y!}(e^h \delta_{g, \xi_0}(p^* \psi)).
\]

We now deduce (6.2.7) since

\[
(6.2.9) \quad \delta_{g, \xi_0}(p^* \psi)
= (g \times \text{id})_t([X \to Y]|_1 \pi_Y^*(\psi_0))
= (g \times \text{id})_t(\psi).
\]

\( \square \)

6.2.2. Remark. — Note that in relative dimension 1, the morphisms \( f_t \) in Proposition 6.2.1 coincide with those constructed in section \( \mathbb{F} \).

6.3. Uniqueness. — The proof is similar to the one in Proposition 6.2.1. Let \( f : Z \to Y \) be a morphism in \( \text{Def}_S \). Consider \( \varphi \) in \( I_S C(Z)^{\text{exp}} \) of the form

\[
(6.3.1) \quad E(g)e^h[X \to Z] \varphi_0
\]

with \( p : X \to Z \) in \( \text{RDef}_Z \), \( g : X \to h[1, 0, 0] \) and \( h : X \to h[0, 1, 0] \) definable morphisms, and \( \varphi_0 \) in \( I_S C(Z) \). We have

\[
(6.3.2) \quad \varphi = p!(E(g)e^h p^* \varphi_0).
\]
Hence, if we denote by \( \delta_{f,g,h} : X \to Y[1,1,0] \) the morphism sending \( x \) to \(((f \circ p)(x), g(x), h(x))\), the axioms force to set

\[
\tag{6.3.3}
\begin{align*}
    f_!(\varphi) := \pi_Y! (\pi_{Y[0,1,0]}! (E(x)e^\xi \delta_{f,g,h!}(p^*\varphi_0)))
\end{align*}
\]

with \( \pi_{Y[0,1,0]} : Y[1,1,0] \to Y[0,1,0] \) and \( \pi_Y : Y[0,1,0] \to Y \) the projections and \( (x,\xi) \) the canonical coordinates on the fibers of \( \pi \). The map \( \pi_Y! \) is determined by (A4) and for the map \( \pi_{Y[0,1,0]}! \) one is forced to use the construction of section 5.

6.4. Preliminaries. — Let \( Z \) be in \( \text{Def}_S \). In Lemma-Definition 3.7.1 we defined push-forwards morphisms

\[
\tag{6.4.1}
\begin{align*}
    \pi! : I_S^C(Z[0,r,m])^{\exp} \longrightarrow I_S^C(Z)^{\exp}
\end{align*}
\]

and in section 5 we constructed a pushforward

\[
\tag{6.4.2}
\begin{align*}
    \pi! : I_S^C(Z[1,0,0])^{\exp} \longrightarrow I_S^C(Z)^{\exp},
\end{align*}
\]

with \( \pi \) denoting the projection.

We may mix these two constructions as follows:

6.4.1. Lemma-Definition. — Let \( Y \) be in \( \text{Def}_S \). Let \( \varphi \) be a Function in \( I_S^C(Y[1,n,r])^{\exp} \). Consider the following commutative diagram of projections

\[
\begin{tikzpicture}
    \node (Y1nr) at (0,0) {\( Y[1,n,r] \)};
    \node (Y00) at (0,-2) {\( Y[1,0,0] \)};
    \node (Y0nr) at (2,-2) {\( Y[0,n,r] \)};
    \node (Y) at (1,-2) {\( Y \)};
    \draw[->] (Y1nr) to node [above] {\( \pi_1 \)} (Y00);
    \draw[->] (Y0nr) to node [below] {\( \pi_2' \)} (Y00);
    \draw[->] (Y1nr) to node [right] {\( \pi_1' \)} (Y0nr);
    \draw[->] (Y0nr) to node [left] {\( \pi_2 \)} (Y);
    \draw[->] (Y1nr) to node [above] {\( \pi \)} (Y0nr);
    \draw[->] (Y0nr) to node [below] {\( \pi' \)} (Y0nr);
\end{tikzpicture}
\]

We have

\[
\pi_2! \pi_1! (\varphi) = \pi_2'! \pi_1'! (\varphi)
\]

and we define \( \pi_1!(\varphi) \) to be the commun value of \( \pi_2! \pi_1! (\varphi) \) and \( \pi_2'! \pi_1'! (\varphi) \).

Proof. — The proof of Proposition-Definition 11.2.2 in [8] carries over to the present setting.

6.5. Fubini for projections \( Y[2,0,0] \to Y \). —

6.5.1. Proposition. — Let \( Y \) be in \( \text{Def}_S \). Let \( p : X \to Y[1,0,0] \) be in \( \text{RDef}_{Y[1,0,0]} \) and \( g : X \to h[1,0,0] \) be a morphism in \( \text{Def}_k \). Denote by \( \pi_Y \) the projection \( Y[1,0,0] \to Y \) and set \( \gamma_g := (\pi_Y \circ p, g) : X \to Y[1,0,0] \). For every Function \( \psi \) in \( I_S^C(Y[1,0,0])^{\exp} \), we have

\[
\pi_{Y!}(E(g)|X \to Y|\psi) = \pi_{Y!}(E(z)\gamma_{g!}(p^*(\psi))).
\]
Proof. — By using a construction with a cell decomposition adapted to \([X \to Y[1,0,0]], \) by pulling back, and by Lemma-Definition 6.4.1, we may assume \(X = Y[1,0,0].\) Similarly, by a cell decomposition construction using Theorem 2.2.2 and by Lemma-Definition 6.4.1, we can reduce to the case where \(g\) is either constant or injective. When \(g\) is constant the statement is clear and when \(g\) is injective it is a direct consequence from Proposition 5.1.3.

Let \(Y\) be in Def\(_S\). For \(i = 1, 2,\) we denote by \(\pi_i : Y[2,0,0] \to Y[1,0,0]\) the projection \((y,z_1,z_2) \mapsto (y,z_i)\) and by \(\pi_Y\) the projection \(Y[1,0,0] \to Y.\)

6.5.2. Proposition. — Let \(\psi\) be in I\(_S\)C\((Y[2,0,0])^e.\) Then
\[
\pi_Y!(\pi_1!(E(z_2)\psi)) = \pi_Y!(\pi_2!(E(z_2)\psi)).
\]

Proof. — We shall use bicells as defined in section 7.4 of \([8,]\). By Proposition 7.4.1 of \([8,]\), any definable subassignment \(Z\) of \(Y[2,0,0]\) admits a bicell decomposition and, furthermore, for any \(\varphi\) in \(C(Z)\) there is a bicell decomposition of \(Z\) adapted to \(\varphi\) in the sense of loc. cit. More generally, for any \(\varphi\) in \(C(Z)^e\), there is a bicell decomposition of \(Z\) adapted to \(\varphi.\) Indeed, this follows from the proof of loc. cit. and the fact that statement (2) in Theorem 2.2.1 still holds when replacing \(C(X)\) by \(C(X)^e.\) Hence, we may assume \(\psi\) is the characteristic function of a bicell \(Z\) in \(Y[2,0,0].\) By the argument given at the beginning of the proof of Proposition 11.2.4 of \([8,]\), we may assume that the bicell \(Z\) is presented by the identity morphism.

Let us consider first the case when \(Z\) is a \((1,1)\)-bicell. We start by the following special case:

6.5.3. Lemma. — Let \(C\) be a definable subassignment of \(Y\) and consider definable morphisms \(c : C \to h[1,0,0], \alpha, \beta : C \to h[0,0,1],\) and \(\xi, \eta : C \to h_{\mathbb{C}_{m,k}}.\) Consider the subassignment \(Z\) of \(Y[2,0,0]\) defined by
\[
\begin{align*}
y \in C \\
\text{ord}(z_1 - z_2) = \alpha(y) \\
\text{ac}(z_1 - z_2) = \xi(y) \\
\text{ord}(z_2 - c(y)) = \beta(y) \\
\text{ac}(z_2 - c(y)) = \eta(y).
\end{align*}
\]

Then
\[
\pi_Y!(\pi_1!(E(z_2)1_Z)) = \pi_Y!(\pi_2!(E(z_2)1_Z)).
\]

Proof of the Lemma. — As in the proof of Lemma 11.2.5 of \([8,]\), we may assume, after partitioning \(C,\) that one of the following condition is satisfied everywhere on \(C:\)

1. \(\beta > \alpha\)
2. \(\beta < \alpha\)
3. \(\beta = \alpha\) and \(\xi + \eta \neq 0\)
4. \(\beta = \alpha\) and \(\xi + \eta = 0.\)
If condition (1) or (3) holds, \( Z \) can be rewritten as a product of two 1-cells, cf. loc. cit., and the result is clear. If (2) is satisfied, then \( Z \) is also defined by

\[
y \in C \\
\text{ord}(z_1 - z_2) = \alpha(y) \\
\text{ac}(z_1 - z_2) = \xi(y) \\
\text{ord}(z_2 - c(y)) = \beta(y) \\
\text{ac}(z_2 - c(y)) = \eta(y).
\]

and one computes

\[
\pi_{1!}(\pi_1!(E(z_2)1_Z)) = E(c)I_{\alpha,\xi}I_{\beta,\eta}
\]

and

\[
\pi_{2!}(\pi_2!(E(z_2)1_Z)) = E(c)L^{-\alpha-1}I_{\beta,\eta}
\]

with \( I_{\alpha,\xi} \), resp. \( I_{\beta,\eta} \), the integral of \( E(z) \) over the subassignment of \( h[1,0,0] \) defined by \( \text{ord}(z) = \alpha \) and \( \text{ac}(z) = \xi \), resp. \( \text{ord}(z) = \beta \) and \( \text{ac}(z) = \eta \). To deduce the requested equality note that \( I_{\beta,\eta} = 0 \) when \( \beta < 0 \), and that when \( \beta \geq 0, \alpha > 0 \), hence \( I_{\alpha,\xi} = L^{-\alpha-1} \). The case of condition (4) also follows from an easy direct computation.

When \( Z \) is a \((1,1)\)-bicell one proceeds similarly as in the proof of Proposition 11.5.4 of [8]. More precisely assume \( Z \) is of the form

\[
y \in C \\
\text{ord}(z_1 - d(y, z_2)) = \alpha(y) \\
\text{ac}(z_1 - d(y, z_2)) = \xi(y) \\
\text{ord}(z_2 - c(y)) = \beta(y) \\
\text{ac}(z_2 - c(y)) = \eta(y).
\]

If \( d \) depends only on \( y \), \( Z \) is a product of 1-cells and the statement is clear. Otherwise \( d(y, z_2) \) can be supposed injective, as in [8], as function of \( z_2 \) for fixed \( y \) and one deduces, with exactly the same proof as in loc. cit., the statement from Lemma 6.5.3 using the change of variables in relative dimension 1 (Proposition 5.1.3).

When \( Z \) is a \((1,0)\)-bicell one proceeds exactly as in loc. cit., using change of variables in relative dimension 1. In the remaining cases of a \((0,1)\) or a \((0,0)\)-bicell, \( Z \) is a product of cells, and the statement is clear.

We may now prove the following version of Fubini Theorem:

\textbf{6.5.4. Proposition.} — Let \( \varphi \) be in \( \mathcal{I}_S C(Y[2,0,0])^{\exp} \). Then

\[
\pi_{1!}(\pi_1!(\varphi)) = \pi_{2!}(\pi_2!(\varphi)).
\]
Proof. — By using a construction as in the proof of Lemma-Definition 6.4.1, but now with a bicell decomposition, we may assume \( \varphi = E(g)\psi \) with \( g : Y[2, 0, 0] \to h[1, 0, 0] \) in \( \text{RDef}_{\mathbb{S}} \) and \( \psi \) in \( \text{I}_{\mathbb{S}}C(Y[2, 0, 0])^e \). By Proposition 6.5.1 we have

\[
\pi_Y!(\pi_1,(\varphi)) = \pi_Y!(\pi_1,(E(g)\psi)) = \pi_Y!(\pi_1,(E(z_2)\gamma_1!(\psi))),
\]

with \( \gamma_1 := (\pi_1, g) : X \to Y[2, 0, 0] \), hence, by Proposition 6.5.2, we have

\[
\pi_Y!(\pi_1,(\varphi)) = \pi_Y!(\pi_2,(E(z_2)\gamma_1!(\psi))) = \pi_Y!(E(z)(\pi_2, \circ \gamma_1!)(\psi))).
\]

The result follows, since by Proposition 6.2.1

\[
(\pi_2, \circ \gamma_1!)(\psi) = (\pi_2 \circ \gamma_1)_!(\psi)
\]

and \( \pi_2 \circ \gamma_1 : X \to Y[1, 0, 0] \) is the morphism \( (\pi, g) \), with \( \pi : Y[2, 0, 0] \to Y \) the projection, which is independent from the order of the two variables in \( h[2, 0, 0] \), again, by Proposition 6.2.1.

6.6. Projections. — Let us first consider the projection \( p : Y[m, 0, 0] \to Y \). Let \( \varphi \) be in \( \text{I}_{\mathbb{S}}C(Y[n, 0, 0])^{\exp} \). If \( m > 1 \), we set, by induction on \( m \), \( p_!(\varphi) = \pi_Y!(\pi_1!(\varphi)) \), where \( \pi_1 : Y[m, 0, 0] \to Y(m, 0, 0] \to Y[0, 0, 0] \) is the projection on the first \( m-1 \) coordinates. By Proposition 6.5.1, this definition is invariant under permutation of coordinates.

In the general case of a projection

\[
p : Y[m, n, r] \to Y,
\]

for any \( \varphi \) in \( \text{I}_{\mathbb{S}}C(Y[m, n, r])^{\exp} \), we set \( p_!(\varphi) := (p_2! \circ p_1!)(\varphi) \) for

\[
Y[m, n, r] \xrightarrow{p_1} Y[m, 0, 0] \xrightarrow{p_2} Y.
\]

It follows from Lemma-Definition 6.4.1, Lemma-Definition 6.4.1 and Proposition 6.5.1, that, for any decomposition of \( p \) into projections

\[
Y[m, n, r] \xrightarrow{p_1} Y[m', n', r'] \xrightarrow{p_2} Y,
\]

with \( m' \leq m, n' \leq n \) and \( r' \leq r \), we have \( p_!(\varphi) = (p_2 \circ p_1!)(\varphi) \) and that the definition of \( p_!(\varphi) \) is invariant under permutation of coordinates.

Now if \( Z \) is a definable subassignment of some \( h[m, n, r] \) and \( \varphi \) is in \( \text{I}_{\mathbb{S}}C(Y \times Z)^{\exp} \) we denote by \( \check{\varphi} \) the Function in \( \text{I}_{\mathbb{S}}C(Y[m, n, r])^{\exp} \) which is obtained from \( \varphi \) by extension by zero outside \( Z \). If \( \varphi = \sum_{1 \leq i,j} \varphi_i[X_i]E(g_i) \), with \( \varphi_i \) in \( \text{I}_{\mathbb{S}}C(Y \times Z)^e \), \( X_i \) in \( \text{RDef}_{\mathbb{S}} \times Z \) and \( g_i : X_i \to h[1, 0, 0] \), we have, with a slight abuse of notations, \( \check{\varphi} = \sum_{1 \leq i,j} \check{j}(\varphi_i)j_j([X_i])E(g_i) \), with \( j : Z \to h[m, n, r] \) the inclusion. Let us write the projection \( p : Y \times Z \to Y \) as \( \pi \circ j \), with \( \pi \) the projection \( Y[m, n, r] \to Y \), and we set

\[
p_!(\varphi) := \pi!(\check{\varphi})
\]

for \( \varphi \) in \( \text{I}_{\mathbb{S}}C(Y \times Z)^{\exp} \).
The projection formula (A3) trivially holds for $p_i$ and also the following form of Fubini’s Theorem.

**6.6.1. Proposition.** — Consider a diagram of projections

$$Y \times Z \times W \xrightarrow{p_1} Y \times Z \xrightarrow{p_2} Y,$$

with $Z$ and $W$ in Def$_k$. Then for any $\varphi$ in I$_S C(Y \times Z \times W)^{exp}$,

$$(p_2 \circ p_1)_!(\varphi) = (p_2! \circ p_1!)(\varphi). \quad \square$$

**6.7. Definable injections.** — Let $i : X \to Y$ be a morphism in Def$_S$ which is a definable injection and let $g : X \to h[1,0,0]$ and $h : X \to h[0,1,0]$ be morphisms. Now if $\varphi = \varphi_0 E(g) e^h [W \to X]$ lies in I$_S C(X)^{exp}$ with $\varphi_0$ in I$_S C(X)$, $W$ in RDef$_X$, and if we write $W'$ for the unique element of RDef$_Y$ such that for each $x \in X$ the fiber $W_x$ equals $W'_{i(x)}$, we set

$$i_!(\varphi) := i_!(\varphi_0) E(g_{W'}) e^{h_{W'}} [W' \to Y],$$

where $h_{W'}$ and $g_{W'}$ are $h$ and $g$ seen on $W'$.

This definition extends uniquely by linearity to give a morphism $i_! : I_S C(X)^{exp} \to I_S C(Y)^{exp}$. Also it is quite clear that if $j : Y \to Z$ is another definable injection in Def$_S$, $(j \circ i)_! = j_! \circ i_!$.

**6.8. General case.** — To define $f_!$ for $f : X \to Y$ a general morphism in Def$_S$, we proceed as in [8]. We decompose $f$ as a composition $f = \pi f \circ i_f$ with $i_f$ the definable injection $X \to X \times Y$ given by $x \mapsto (x, f(x))$ and $\pi f : X \times Y \to Y$ the canonical projection, and we set $f_! = \pi f_! \circ i_f_!$.

It is quite clear that when $f$ is an injection the new definition coincides with the previous one. Also, when $f$ is a projection $Y \times Z \to Y$, the new definition coincides with the previous one. Indeed, the analogue of Lemma 11.5.2 of [8] holds for similar reasons in the present setting, so the proof in Lemma 11.6.1 of [8] extends directly.

**6.9. End of proof.** — We still have to check that if $f : X \to Y$ and $g : Y \to Z$ are morphisms in Def$_S$, then $g_! \circ f_! = (g \circ f)_!$. This is proved in a formal way exactly as in Proposition 11.7.1 of [8], since the analogue of Lemma 11.7.2 in [8] holds in the present setting. Axioms (A1)-(A5) follow directly by construction.

7. Fourier transformation

Let $p : X \to \Lambda$ be a morphism in Def$_k$, with all fibers of relative dimension $d$. We shall denote by $I_\Lambda(X)^{exp}$ or $I_{\bar{\Lambda}}(X)^{exp}$ the $C(\Lambda)^{exp}$-module of functions $\varphi$ in $C(X)^{exp}$ whose class $[\varphi]$ in $C^d(X \to \Lambda)^{exp}$ lies in I$_\Lambda C(Z \to \Lambda)^{exp}$. We shall also write $\mu_\Lambda(\varphi)$ or $\mu_p(\varphi)$ to denote the function $\mu_\Lambda([\varphi])$ in $C(\Lambda)^{exp}$.
7.1. Fourier transformation over the residue field. — Fix \( \Lambda \) in \( \text{Def}_k \) and an integer \( d \geq 0 \). We consider the subassignment \( \Lambda[0,2d,0] \) with first \( d \) residue field coordinates \( x = (x_1, \ldots, x_d) \) and last \( d \) residue coordinates \( y = (y_1, \ldots, y_d) \) and denote by \( p_1 : \Lambda[0,2d,0] \to \Lambda[0,d,0] \) and \( p_2 : \Lambda[0,2d,0] \to \Lambda[0,d,0] \) the projection onto the \( x \)-variables and \( y \)-variables, respectively. We consider the function \( e(xy) := e(\sum_{1 \leq i \leq d} x_i y_i) \) in \( C(\Lambda[0,2d,0])^{\exp} \).

We define the Fourier transform

\[
(7.1.1) \quad f : C(\Lambda[0,d,0])^{\exp} \to C(\Lambda[0,d,0])^{\exp}
\]

by

\[
(7.1.2) \quad f(\varphi) := p_1!\Lambda[0,d,0](\{e(xy)p_2^*(\varphi)\}),
\]

for \( \varphi \in C(\Lambda[0,d,0])^{\exp} \). The morphism \( f \) is \( C(\Lambda) \)-linear.

For \( \varphi \) in \( C(\Lambda[0,d,0])^{\exp} \) we write \( \varphi \) for \( \iota^*\varphi \), with \( \iota : \Lambda[0,d,0] \to \Lambda[0,d,0] \) the \( \Lambda \)-morphism sending \( x \) to \(-x\).

7.1.1. Theorem. — Let \( \varphi \) be in \( C(\Lambda[0,d,0])^{\exp} \). We have

\[
(f \circ f)(\varphi) = L^d \varphi.
\]

Proof. — The proof is essentially the same as the standard one for finite fields. More precisely, we work on \( \Lambda[0,3d,0] \) with coordinates \( (x_1, \ldots, x_d, y_1, \ldots, y_d, z_1, \ldots, z_d) \). We shall denote by \( x : \Lambda[0,3d,0] \to \Lambda[0,d,0] \), \( (x,y) : \Lambda[0,3d,0] \to \Lambda[0,2d,0] \) the projections onto the corresponding components, etc. If \( f \) is a function on \( \Lambda[0,d,0] \) we shall write \( f(x) \) instead of \( x^*f \), etc. By induction and Fubini Theorem (cf. Remark [3.2]) we may assume \( d = 1 \).

Let \( \varphi \) be in \( C(\Lambda[0,d,0])^{\exp} \). We have

\[
(7.1.3) \quad (f \circ f)(\varphi) = \mu_x[e(y(x+z))\varphi(z)] = \mu_x[e(yu)\varphi(u-x)],
\]

after performing the change of variables \( (x,y,z) \mapsto (x,y,u = x+z) \). Since

\[
(7.1.4) \quad L_u \varphi(x) = \mu_x[1_{u=0}1_{y=y}\varphi(-x)],
\]

we have

\[
(7.1.5) \quad ((f \circ f)(\varphi) - L \varphi)(x) = \mu_x[1_{u \neq 0}e(yu)\varphi(u-x)],
\]

which, after performing the change of variables \( (x,y,u) \mapsto (x,w = yu,u) \), may be rewritten as

\[
(7.1.6) \quad ((f \circ f)(\varphi) - L \varphi)(x) = \mu_x[1_{u \neq 0}e(w)\varphi(u-x)],
\]

whose right hand side is zero by Fubini Theorem and relation \([3.1.4]\). □
7.2. Fourier transformation over the valued field. — Fix $\Lambda$ in $\text{Def}_k$ and an integer $d \geq 0$. We consider the subassignment $\Lambda[2d,0]$ with first $d$ valued field coordinates $x = (x_1, \ldots, x_d)$ and last $d$ valued field coordinates $y = (y_1, \ldots, y_d)$ and denote by $p_1 : \Lambda[2d,0] \to \Lambda[d,0]$ and $p_2 : \Lambda[2d,0] \to \Lambda[d,0]$ the projection onto the $x$-variables and $y$-variables, respectively. We consider the function $E(xy) := E(\sum_{1 \leq i \leq d} x_i y_i)$ in $C(\Lambda[2d,0])^{\exp}$.

7.2.1. Lemma. — Let $\varphi$ be in $\mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp}$. The class $[E(xy)p_2^*(\varphi)]$ of $E(xy)p_2^*(\varphi)$ in $C^d(p_1 : \Lambda[2d,0] \to \Lambda[d,0,0])^{\exp}$ is integrable rel. $p_1$.

Proof. — Indeed, it follows by construction that, if $\psi$ is a function in $C(\Lambda[d,0,0])$ whose class $[\psi]$ in $C^d(\Lambda[d,0,0] \to \Lambda)$ is $\Lambda$-integrable, the class of the pull-back $p_2^*(\psi)$ in $C^d(p_1 : \Lambda[2d,0] \to \Lambda[d,0,0])$ is integrable rel. $p_1$. The statement follows.

Thanks to Lemma 7.2.1, one may define the Fourier transformation

(7.2.1) \[ \mathfrak{F} : \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \to \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \]

for $\varphi$ in $\mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp}$. The morphism $\mathfrak{F}$ is $\mathcal{C}(\Lambda)^{\exp}$-linear.

7.3. — Let us compute some simple examples. Consider definable functions $\alpha : \Lambda \to \mathbb{Z}$ and $\xi = (\xi_1, \ldots, \xi_d) : \Lambda \to h[0,d,0]$ with $\xi_i$ nowhere zero and set

\[ Z_\alpha := \{ (\lambda, x = (x_1, \ldots, x_d)) \in \Lambda[d,0,0] \mid \text{ord}(x_i) \geq \alpha(\lambda) \}, \]
\[ W_\alpha := \{ (\lambda, x = (x_1, \ldots, x_d)) \in \Lambda[d,0,0] \mid \text{ord}(x_i) = \alpha(\lambda) \}, \]
\[ W_{\alpha,\xi} := \{ (\lambda, x = (x_1, \ldots, x_d)) \in \Lambda[d,0,0] \mid \text{ord}(x_i) = \alpha(\lambda), \overline{\alpha}(x_i) = \xi_i(\lambda) \}, \]
\[ \varphi_\alpha := 1_{Z_\alpha}, \quad \psi_\alpha := 1_{W_\alpha}, \quad \text{and} \quad \psi_{\alpha,\xi} := 1_{W_{\alpha,\xi}}. \]

7.3.1. Proposition. — The following formulas hold:

1. $\mathfrak{F}(\varphi_\alpha) = L^{-\alpha} \varphi_{-\alpha+1}$.
2. $\mathfrak{F}(\psi_\alpha) = L^{-\alpha} \varphi_{-\alpha+1} - L^{-\alpha-d} \varphi_{-\alpha}$.
3. $\mathfrak{F}(\psi_{\alpha,\xi}) = L^{-\alpha-d} (\varphi_{-\alpha+1} + e(i) \psi_{-\alpha})$, with $i$ the morphism $\Lambda[d,0,0] \to \Lambda[d,1,0]$ given by $(\lambda, x) \mapsto (\lambda, x, \sum_i \xi_i(\lambda) \overline{\alpha} x_i)$.

Proof. — By induction on $d$, we may assume $d = 1$. Let us start by proving (3). It is enough to check that the restriction of $\mathfrak{F}(\psi_{\alpha,\xi})$ to the subassignment defined by $\text{ord} x = \beta$ and $\overline{\alpha} x = \eta$ is equal to 0 if $\alpha + \beta < 0$, to $L^{-\alpha}$ if $\alpha + \beta > 0$, and is equal to $e(\xi_\eta)L^{-\alpha - 1}$ if $\alpha + \beta = 0$. The case $\alpha + \beta < 0$ follows from (A5) of Theorem 1.3. The cases $\alpha + \beta > 0$ and $\alpha + \beta = 0$ follow from relation (3.3) and the construction in [8]. Cases (1) and (2) are more easy. The reader may also choose to prove first the case of $\alpha = 0$ and deduce the case of general $\alpha$ from it.

We calculate some more examples.

7.3.2. Lemma. — Assume $d = 1$ and let $\gamma : \Lambda \to \mathbb{Z}$ and $\xi : \Lambda \to h[0,1,0]$ be definable functions. Then
(1) If $\gamma > 0$ on $\Lambda$, $\mu_\Lambda(\psi_{\gamma, \xi}E(x)) = L^{-\gamma - 1}$, $\mu_\Lambda(\psi_{\gamma}E(x)) = (L - 1)L^{-\gamma - 1}$ and $\mu_\Lambda(\varphi_{\gamma}E(x)) = L^{-\gamma}$.

(2) If $\gamma < 0$ on $\Lambda$, $\mu_\Lambda(\psi_{\gamma, \xi}E(x)) = \mu_\Lambda(\psi_{\gamma}E(x)) = 0$.

(3) If $\gamma = 0$ on $\Lambda$, $\mu_\Lambda(\psi_{\gamma, \xi}E(x)) = e(\xi)L^{-1}$ and $\mu_\Lambda(\psi_{\gamma}E(x)) = -L^{-1}$.

**Proof.** — Statement (1) and the first part of (3) are obvious from relation (3.1.3) and the construction in $\mathbb{S}$, and (2) follows from (A5) of Theorem 4.1.1.

The last part of (3) follows from the first part using cell decomposition, since, by relation (3.1.4), $\mu_\Lambda(i\i^*e(\xi)) = -1$, with $\xi$ the residue field variable on $\Lambda[0, 1, 0]$ and $i$ the inclusion of the subassignment defined by $\xi \neq 0$ in $\Lambda[0, 1, 0]$. □

If follows readily from Proposition 7.3.1 that

(7.3.1) \[ \mathfrak{F} \circ \mathfrak{F}(\varphi_\alpha) = L^{-d} \varphi_\alpha \]

and

(7.3.2) \[ \mathfrak{F} \circ \mathfrak{F}(\psi_\alpha) = L^{-d} \psi_\alpha. \]

The corresponding statement for $\psi_{\alpha, \xi}$ will follow from the general Fourier inversion for Schwartz-Bruch functions we shall prove in Theorem 7.5.1. Though not at all necessary, let us provide a direct proof of that fact:

**7.3.3. Proposition.** — The following holds

\[ \mathfrak{F} \circ \mathfrak{F}(\psi_{\alpha, \xi}) = L^{-d} \psi_{\alpha, -\xi}. \]

**Proof.** — We may assume $d = 1$. By (1) and (3) of Proposition 7.3.1, it is enough to calculate $\mathfrak{F}(e(i)\psi_{\alpha})$, with $i$ the morphism $\Lambda[1, 0, 0] \to \Lambda[1, 1, 0]$ given by $(\lambda, x) \mapsto (\lambda, x, \xi(\lambda)\exp x)$. But this can be done similarly as (3) of Proposition 7.3.1 and the last part of (3) of Lemma 7.3.2. □

**7.4. Convolution.** — We denote by $x + y$ the morphism $\Lambda[2d, 0, 0] \to \Lambda[d, 0, 0]$ given by $(x_1, \ldots, x_d, y_1, \ldots, y_d) \mapsto (x_1 + y_1, \ldots, x_d + y_d)$. We shall also work on $\Lambda[3d, 0, 0]$ with coordinates $(x_1, \ldots, x_d, y_1, \ldots, y_d, z_1, \ldots, z_d)$. We shall denote by $x : \Lambda[3d, 0, 0] \to \Lambda[d, 0, 0]$, $(x, y) : \Lambda[3d, 0, 0] \to \Lambda[2d, 0, 0]$ the projections onto the corresponding components, etc. If $f$ is a function on $\Lambda[0, 0, 0]$ we shall write $f(x)$ instead of $x^*f$, etc.

**7.4.1. Proposition-Definition.** — Let $f$ and $g$ be two functions in $\mathcal{I}_\Lambda(\Lambda[d, 0, 0])^{\text{exp}}$. The function $p_1^*(f)p_2^*(g)$ lies in $\mathcal{I}_{x+y}(\Lambda[2d, 0, 0])^{\text{exp}}$ and the function

\[ f \ast g := \mu_{x+y}(p_1^*(f)p_2^*(g)) \]

lies in $\mathcal{I}_\Lambda(\Lambda[d, 0, 0])^{\text{exp}}$, where $p_1$ and $p_2$ are as in section 7.2.

**Proof.** — It follows directly from Theorem 14.1.1 in $\mathbb{S}$ that, if $\varphi$ and $\psi$ are functions in $\mathcal{C}(\Lambda[0, 0, 0])$ whose class in $C^d(\Lambda[d, 0, 0] \to \Lambda)$ are in $I_\Lambda C(\Lambda[d, 0, 0] \to \Lambda)$, then the class of $p_1^*(\varphi)p_2^*(\psi)$ in $C^d(\Lambda[2d, 0, 0] \to \Lambda)$ lies in $I_\Lambda C(\Lambda[2d, 0, 0] \to \Lambda)$. 
One deduces that the function \( p_1^*(f)p_2^*(g) \) lies in \( \mathcal{I}_\Lambda(\Lambda[2d,0,0])^{\exp} \), hence also in \( \mathcal{I}_{x+y}(\Lambda[2d,0,0])^{\exp} \). Since, by Fubini Theorem,

\[
(7.4.1) \quad \mu_\Lambda(p_1^*(f)p_2^*(g)) = \mu_\Lambda(p_{x+y}^*(f)p_2^*(g)),
\]

it follows that \( f*g \) lies in \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \).

\[\square\]

7.4.2. Proposition. — The convolution product \( (f,g) \mapsto f*g \) is \( \mathcal{C}(\Lambda)^{\exp} \)-linear and it endows \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \) with an associative and commutative law.

Proof. — \( \mathcal{C}(\Lambda)^{\exp} \)-linearity and commutativity being clear, let us check associativity. This follows from the fact that, if \( f \), \( g \) and \( h \) are be functions in \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \),

\[
(7.4.2) \quad (f*g) \ast h = \mu_{x+y+z}(p_1^*(f)p_2^*(g)p_3^*(h)).
\]

by Fubini Theorem.

\[\square\]

7.4.3. Proposition. — Let \( f \) and \( g \) be two functions in \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \). Then

\[
\mathfrak{F}(f \ast g) = \mathfrak{F}(f) \mathfrak{F}(g).
\]

Proof. — The proof is just the same as the usual one. Let us consider the function \( E(x(y+z))f(y)g(z) \) on \( \Lambda[3d,0,0] \). It is integrable rel. \( x \), and by Fubini Theorem we have

\[
(7.4.3) \quad \mu_x(E(x(y+z))f(y)g(z)) = \mu_x((E(xy)f(y))(E(xz)g(z))) = \mathfrak{F}(f)\mathfrak{F}(g).
\]

On the other hand, by the change of variables formula, using the change of variables \( (x,y,z) \mapsto (x,u = y+z,z) \), \( \mu_x(E(x(y+z))f(y)g(z)) \) may be expressed as

\[
(7.4.4) \quad \mu_x(E(xu)\mu_{x,u}(f(u-z)g(z))) = \mathfrak{F}(f \ast g),
\]

which ends the proof.

\[\square\]

For \( \varphi \) in \( \mathcal{C}(\Lambda[d,0,0])^{\exp} \) we write \( \varphi^* \) for \( \iota^*(\varphi) \), with \( \iota : \Lambda[d,0,0] \to \Lambda[d,0,0] \) the \( \Lambda \)-morphism sending \( x \) to \( -x \).

We have the following partial Fourier inversion:

7.4.4. Proposition. — Let \( \varphi \) be a function in \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \). For every \( \alpha \) in \( \mathbb{Z} \), \( \varphi_\alpha \mathfrak{F}(\varphi) \) lies in \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \) and

\[
\mathfrak{F}(\varphi_\alpha \mathfrak{F}(\varphi)) = L^{-\alpha d} \varphi \ast \varphi_{-\alpha+1}.
\]

Proof. — We shall work on \( \Lambda[3d,0,0] \), keeping notations and conventions from the proof of Proposition 7.4.3. The integrability of \( \varphi_\alpha \mathfrak{F}(\varphi) \) follows from the fact that the function \( E(yz)\varphi_\alpha(y)\varphi(z) \) on \( \Lambda[2d,0,0] \) lies in \( \mathcal{I}_\Lambda(\Lambda[2d,0,0])^{\exp} \). Let us consider the
function \( E(y(x + z))\varphi_\alpha(y)\varphi(z) \) on \( \Lambda[3d, 0, 0] \). It is integrable rel. \( x \), and by Fubini Theorem we have

\[
\mu_x(E(y(x + z))\varphi_\alpha(y)\varphi(z)) = \mu_x(\mu_{(x,z)}(E(y(x + z))\varphi_\alpha(y)\varphi(z)))
\]

(7.4.5)

\[
= \mu_x(\varphi_\alpha(x)E(xy)\mu_{(x,y)}(E(yz)\varphi(z)))
\]

\[
= \mu_x(E(xy)\varphi_\alpha(y)\mathcal{F}(\varphi)(y))
\]

\[
= \mathcal{F}(\varphi_\alpha \mathcal{F}(\varphi)).
\]

(7.4.6)

On the other hand, performing the change of variables \( (x, y, z) \mapsto (u = x + z, y, z) \), we have, by the change of variables formula,

\[
\mu_x(E(y(x + z))\varphi_\alpha(y)\varphi(z)) = \mu_x(\mu_{(x,z)}(E(y(x + z))\varphi_\alpha(y)\varphi(z)))
\]

\[
= \mu_{u-z}(\mu_{(u,z)}(E(uy)\varphi_\alpha(y)\varphi(z)))
\]

\[
= \mu_{u-z}(\varphi(z)\mu_{(u,z)}(E(uy)\varphi_\alpha(y)))
\]

\[
= \mu_{u-z}(\varphi(z)\mathcal{F}(\varphi_\alpha)(u))
\]

\[
= \mu_{u+z}(\varphi(z)\mathcal{F}(\varphi_\alpha)(u))
\]

\[
= \varphi \ast \mathcal{F}(\varphi_\alpha),
\]

which concludes the proof. \( \Box \)

7.5. **Schwartz-Bruhat functions.** — We define the space \( S_\Lambda(\Lambda[d, 0, 0])^{exp} \) of Schwartz-Bruhat functions over \( \Lambda \) as the \( C(\Lambda)^{exp} \)-submodule of \( I_\Lambda(\Lambda[d, 0, 0])^{exp} \) consisting of functions \( f \) such that

\[
f \cdot \varphi_\alpha = f \quad \text{for } \alpha \ll 0
\]

(7.5.1)

and

\[
f \ast \varphi_\alpha = L^{-\alpha d} f \quad \text{for } \alpha \gg 0.
\]

(7.5.2)

Condition (7.5.1) stands for “compactly supported” and condition (7.5.2) for “locally constant”. Here the quantifier \( \alpha \ll 0 \) in (7.5.1), resp. \( \alpha \gg 0 \) in (7.5.2), means there exists a definable function \( \alpha_0 : \Lambda \to \mathbb{Z} \) such that (7.5.1), resp. (7.5.2), holds for every definable function \( \alpha : \Lambda \to \mathbb{Z} \) such that \( \alpha \leq \alpha_0 \), resp. \( \alpha \geq \alpha_0 \).

**7.5.1. Theorem.** — Fourier transformation induces an isomorphism

\[
\mathcal{F} : S_\Lambda(\Lambda[d, 0, 0])^{exp} \simeq S_\Lambda(\Lambda[d, 0, 0])^{exp}
\]

and, for every \( \varphi \) in \( S_\Lambda(\Lambda[d, 0, 0])^{exp} \),

\[
(\mathcal{F} \circ \mathcal{F})(\varphi) = L^{-d} \varphi.
\]

(7.5.3)

**Proof.** — Let \( \varphi \) be in \( S_\Lambda(\Lambda[d, 0, 0])^{exp} \). Let us note that, for \( \alpha \ll 0 \),

\[
\mathcal{F}(\varphi) \varphi_\alpha = \mathcal{F}(\varphi).
\]

(7.5.4)

Indeed, by Proposition 7.3.3 and Proposition 7.3.1 (1), for \( \alpha \gg 0 \),

\[
\mathcal{F}(\varphi) = \mathcal{F}(\varphi \ast \varphi_\alpha) L^{\alpha d} = \mathcal{F}(\varphi) \varphi_{\alpha+1}.
\]

(7.5.5)
It follows from Proposition 7.4.4 that \( \mathfrak{F}(\varphi) \) lies in \( \mathcal{I}_\Lambda(\Lambda[0,0])^{\exp} \) and that
\[
(7.5.7) \quad \mathfrak{F}(\mathfrak{F}(\varphi)) = L^{-ad} \varphi \ast \varphi_{-a+1},
\]
for \( \alpha \ll 0 \). Since \( \varphi \) lies in \( \mathcal{S}_\Lambda(\Lambda[0,0])^{\exp} \), \( \varphi \) also, hence
\[
(7.5.8) \quad \varphi \ast \varphi_{-a+1} = L^{(a-1)d} \varphi
\]
for \( \alpha \ll 0 \), and we deduce (7.5.10). So we are left with proving that \( \mathfrak{F}(\varphi) \) lies in \( \mathcal{S}_\Lambda(\Lambda[0,0])^{\exp} \). It is enough to check that, for \( \alpha \ll 0 \),
\[
(7.5.9) \quad \mathfrak{F}(\varphi) L^{-(a+1)d} = \mathfrak{F}(\varphi) \ast \varphi_{-a+1},
\]
which follows from the relations
\[
(7.5.10) \quad \mathfrak{F}(\mathfrak{F}(\varphi))) = \mathfrak{F}(\varphi \mathfrak{F}(\varphi))) = L^{-ad} \mathfrak{F}(\varphi) \ast \varphi_{-a+1},
\]
for \( \alpha \ll 0 \) by Proposition 7.4.4 and, by (7.5.4),
\[
(7.5.11) \quad \mathfrak{F}(\mathfrak{F}(\varphi))) = L^{-d} \mathfrak{F}(\varphi).
\]

Now we can prove Fourier inversion for integrable functions with integrable Fourier transform.

7.5.2. Theorem. — Let \( \varphi \) be in \( \mathcal{I}_\Lambda(\Lambda[0,0])^{\exp} \). We assume \( \mathfrak{F}(\varphi) \) belongs also to \( \mathcal{I}_\Lambda(\Lambda[0,0])^{\exp} \). Then the functions \( (\mathfrak{F} \circ \mathfrak{F})(\varphi) \) and \( L^{-d} \varphi \) have the same class in \( C^0(\Lambda[0,0] \to \Lambda) \).

Proof. — By induction on \( d \) we may assume \( d = 1 \). Take \( \varphi \) in \( \mathcal{I}_\Lambda(\Lambda[1,0])^{\exp} \). By Lemma 7.5.3 and additivity, we may assume there exists a 1-cell \( \lambda : Z \to Z_C \subset \Lambda[1,s,r] \), such that, denoting by \( i \) the inclusion \( Z \to \Lambda[1,0] \) and by \( j \) the inclusion \( Z_C \to \Lambda[1,s,r] \), \( \varphi = i^*(\varphi) \) and \( \psi := j_!(i^*(\varphi)) \) lies in \( \mathcal{S}_\Lambda(\Lambda[0,s],(\Lambda[1,r,s])^{\exp} \). Since, denoting by \( \pi \) the projection \( \Lambda[1,r,s] \to \Lambda \), \( \varphi = \pi_!(\psi) \), the result follows formally from Lemma 7.5.3 and Theorem 7.5.4.

7.5.3. Lemma. — For every \( \varphi \) in \( \mathcal{I}_\Lambda(\Lambda[1,0])^{\exp} \) there exists a cell decomposition of \( \Lambda[1,0] \) such that, for every 1-cell \( \lambda : Z \to Z_C \subset \Lambda[1,s,r] \), the function \( j_!(i^*(\varphi)) \) lies in \( \mathcal{S}_\Lambda(\Lambda[0,r,s],(\Lambda[1,r,s])^{\exp} \), where \( i \) denotes the inclusion \( Z \to \Lambda[1,0] \) and \( j \) the inclusion \( Z_C \to \Lambda[1,s,r] \).

Proof. — Follows easily from 6.1 or even from Theorem 2.2.1.

7.5.4. Lemma. — For \( r \) and \( s \) in \( \mathbb{N} \), denote by \( \pi \) the projection \( \Lambda[d,r,s] \to \Lambda[d,0,0] \) and recall notation from 3.6. For any \( \varphi \) in \( \mathcal{I}_\Lambda(\Lambda[0,r,s],(\Lambda[0,r,s])^{\exp} \), if the function \( \pi_!(\varphi) \) lies in \( \mathcal{I}_\Lambda(\Lambda[d,0,0])^{\exp} \), then
\[
\mathfrak{F}(\pi_!(\varphi)) = \pi_!(\mathfrak{F}(\varphi)).
\]

Proof. — Follows from the fact that \( \mu_{\pi_!} \) commutes with \( \pi_! \).
8. Exponential integrals over the $p$-adics

8.1. Definable sets over the $p$-adics. — Let $K$ be a finite field extension of $\mathbb{Q}_p$ with valuation ring $R$. We recall the notion of (globally) subanalytic subsets of $K^n$ and of semialgebraic subsets of $K^n$. Let $\mathcal{L}_{\text{Mac}} = \{0, +, -, \cdot, \{P_n\}_{n>0}\}$ be the language of Macintyre and $\mathcal{L}_{\text{an}} = \mathcal{L}_{\text{Mac}} \cup \{-1, \cup_{m>0}K\{x_1, \ldots, x_m\}\}$, where $P_n$ stands for the set of $n$th powers in $K^\times$, where $K\{x_1, \ldots, x_m\}$ is the ring of restricted power series over $K$ (that is, formal power series converging on $R^m$), and each element $f$ of $K\{x_1, \ldots, x_m\}$ is interpreted as the restricted analytic function $K^m \to K$ given by

\[
x \mapsto \begin{cases} f(x) & \text{if } x \in R^m \\
0 & \text{else.} \end{cases}
\]

By subanalytic we mean $\mathcal{L}_{\text{an}}$-definable with coefficients from $K$ and by semialgebraic we mean $\mathcal{L}_{\text{Mac}}$-definable with coefficients from $K$. Note that subanalytic, resp. semialgebraic, sets can be given by a quantifier free formula with coefficients from $K$ in the language $\mathcal{L}_{\text{Mac}}$, resp. $\mathcal{L}_{\text{an}}$.

In this section we let $\mathcal{L}$ be either the language $\mathcal{L}_{\text{Mac}}$ or $\mathcal{L}_{\text{an}}$ and by $\mathcal{L}$-definable we will mean semialgebraic, resp. subanalytic when $\mathcal{L}$ is $\mathcal{L}_{\text{Mac}}$, resp. $\mathcal{L}_{\text{an}}$. Everything in this section will hold for both languages and we will give the appropriate references for both languages where needed.

For each definable set $X \subset K^n$ let $\mathcal{C}(X)$ be the $\mathbb{Q}$-algebra of functions on $X$ generated by functions $|f|$ and $\text{ord}(f)$ for all definable functions $f : X \to K^\times$.(1)

For a $\mathcal{L}$-definable set $X$, let $\mathcal{C}^{\leq d}(X)$ be the ideal of $\mathcal{C}(X)$ generated by the characteristic functions $1_Z$ of $\mathcal{L}$-definable subsets $Z \subset X$ of dimension $\leq d$. (For the definition of the dimension of $\mathcal{L}$-definable sets, see [19] and [17].) Note that the support of a function in $\mathcal{C}(X)$ is in general not $\mathcal{L}$-definable, cf. the function $(x, y) \mapsto |x| - \text{ord}(y)$ on $K \times K^\times$.

By $\mathcal{C}^d(X)$ we denote the quotient

\[
\mathcal{C}^d(X) := \mathcal{C}^{\leq d}(X)/\mathcal{C}^{\leq d-1}(X).
\]

Finally we set

\[
\mathcal{C}(X) := \bigoplus_{d \geq 0} \mathcal{C}^d(X).
\]

It is a module over $\mathcal{C}(X)$. If $\varphi$ is in $\mathcal{C}(X)$ with support contained in a $\mathcal{L}$-definable set of dimension $d$, we denote by $[\varphi]_d$ its image in $\mathcal{C}^d(X)$.

8.2. The $p$-adic measure. — Suppose that $X \subset K^n$ is a $\mathcal{L}$-definable set of dimension $d \geq 0$. The set $X$ contains a definable nonempty open submanifold $X' \subset K^n$ such that $X \setminus X'$ has dimension $< d$, cf. [17]. There is a canonical $d$-dimensional measure on $X'$ coming from the embedding in $K^n$, which is constructed

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(1) Instead of taking the $\mathbb{Q}$-algebra we could as well take the $\mathbb{Z}[1/q, \{1/(1-q^i)\}_{i<0}]$-algebra, with $q$ the residue cardinality of $K$. 
as follows, cf. [30]. For each \(d\)-element subset \(J\) of \(\{1, \ldots, n\}\), with \(j_i < j_{i+1}\), \(j_i\) in \(J\), let \(dx_J\) be the \(d\)-form \(dx_{j_1} \wedge \ldots \wedge dx_{j_d}\) on \(K^n\), with \(x = (x_1, \ldots, x_n)\) standard global coordinates on \(K^n\). Let \(x_0\) be a point on \(X'\) such that \(x_I\) are local coordinates around \(x_0\) for some \(I \subset \{1, \ldots, n\}\). For each \(d\)-element subset \(J\) of \(\{1, \ldots, n\}\) let \(g_J\) be the \(L\)-definable function determined at a neighborhood of \(x_0\) in \(X'\) by \(g_J dx_J = dx_J\). There is a unique volume form \(|\omega_0|_{X'}\) on \(X'\) which is locally equal to \((\max_J |g_J|)|dx_J|\) around every point \(x_0\) in \(X'\). Indeed, \(|\omega_0|_{X'}\) is equal to \(\sup_J |dx_J|\). The canonical \(d\)-dimensional measure on \(X'\), cf. [30] [28], is the one induced by the volume form \(|\omega_0|_{X'}\). We extend this measure to \(X\) by zero and denote it by \(\mu^d\).

This measure allows us to define the subgroup \(IC^d(X)\) of \(C^d(X)\) for a \(L\)-definable set \(X\) of dimension \(d\), as the group generated by elements \([\varphi]_d\) with \(\varphi\) in \(C(X)\) integrable for \(\mu^d\). We define \(IC^e(X)\) for general \(e\) as the subgroup of \(C^e(X)\) consisting of elements \([\varphi]_e\) with \(\varphi\) with support contained in a \(L\)-definable subset \(Z \subset X\) of dimension \(e\) and with \([\varphi|Z]_e\) in \(IC^e(Z)\). Finally, we define the graded group \(IC(X)\) as \(\oplus_e IC^e(X)\).

### 8.3. Jacobian

Using the pullback of differential forms under analytic maps, it is possible to define the norm of the Jacobian \(|\text{Jac} f|\) of a \(L\)-definable bijection \(f : X \subset K^n \to Y \subset K^m\) as follows. There exists definable \(K\)-analytic manifolds \(X' \subset X\) and \(Y' \subset Y\) such that \(X \setminus X'\) and \(Y \setminus Y'\) have dimension < \(d\) with \(d = \dim X\) and such that \(f|_{X'}\) is a \(K\)-bi-analytic bijection onto \(Y'\). For subsets \(I\) and \(J\) of \(\{1, \ldots, n\}\) and \(\{1, \ldots, m\}\) respectively, we denote by \(U_{I,J}\) the definable subset of \(X'\) consisting of points \(x_0\) such that \(|dx_I|\) coincides with \(|\omega_0|_{X'}\) on a neighborhood of \(x_0\) and \(|dy_J|\) coincides with \(|\omega_0|_{Y'}\) on a neighborhood of \(f(x_0)\). On \(U_{I,J}\) we may write \(f^*(dy_J) = g_{I,J} dx_J\). The functions \([g_{I,J}]\) are constructible on \(U_{I,J}\) and there exists a unique constructible function \(h\) on \(X'\) restricting to \([g_{I,J}]\) on each \(U_{I,J}\). We define \(|\text{Jac} f|\) as the class of \(h\) in \(C^d(X)\) which does not depend on the choices made.

The \(p\)-adic change of variables formula (cf. [28]) may be restated as follows:

#### 8.3.1. Proposition

Let \(f : X \subset K^n \to Y \subset K^m\) be a \(L\)-definable bijection, with \(d = \dim X\). For every measurable subset \(A\) of \(Y\) one has

\[
\mu^d(A) = \int_{f^{-1}(A)} |\text{Jac} f| \mu^d.
\]

8.3.2. For the proof of Theorem 8.3.3 below we shall need the following variant of \(|\text{Jac} f|\). Let \(X\) a definable subset of \(Y \times K^n\) for \(Y\) a definable subset of \(K^m\) and consider the morphism \(f : X \to Y\) induced by projection. Assume first \(X\) is of dimension \(r\), \(Y\) of dimension \(s\), \(f\) is surjective and all fibers of \(f\) have dimension \(r - s\). In this setting we define a constructible function \(\delta\) defined almost everywhere on \(X\) as follows. We can choose (cf. [17]) definable manifolds \(X' \subset X\) and \(Y' \subset Y\) such that \(X \setminus X'\) has dimension < \(r\), \(Y \setminus Y'\) has dimension < \(s\), \(f\) restricts to a locally analytic morphism \(f' : X' \to Y'\) and for every point \(y\) in \(Y'\), \(f^{-1}(y) \setminus f'^{-1}(y)\) is of dimension < \(r - s\), and such that \(f'\) is regular (that is, the Jacobian matrix has everywhere maximal rank). Denote by \(y_i\) the coordinates on \(K^m\) and by \(z_i\) the
coordinates on $K^n$. Consider subsets $I, I'$ of $\{1, \ldots, m\}$ and $J, J'$ of $\{1, \ldots, n\}$, and denote by $U_{I, I', J'}$ the set of points $x$ of $X'$ such that on a neighborhood of $x$, $|\omega_0|_{X'}$ coincides with $|dy_I \wedge dz_J|$, $|\omega_0|_{\pi^{-1}(f(x))}$ coincides with $|dz_{J'}|$, and on a neighborhood of $f(x)$, $|\omega_0|_{Y'}$ coincides with $|dy_J|$. On $U_{I, I', J'}$ we may write

$$dy_I \wedge dz_J = g_{I, I', J'} dy_I \wedge dz_J,$$

with $g_{I, I', J'}$ definable. There is a unique constructible function $g$ on $X'$ restricting to $|g_{I, I', J'}|$ on $X'$. We denote its class in $C^\infty(X)$, which is independent of the choices made, by $\delta(f)$. Note that when $f$ is an isomorphism $\delta(f) = |\text{Jac} f|$.

The proof of the following chain rule is clear:

8.3.3. Lemma. — Let $Z$ be a definable subset of dimension $t$ of $K^m$, $Y$ be a definable subset of dimension $s$ of $Z \times K^n$ and $X$ be a definable subset of dimension $r$ of $Y \times K^n$. Assume the morphisms $f : X \to Y$ and $g : Y \to Z$ are induced by projections and are surjective, and that all their fibers have dimension $r - s$ and $s - t$, respectively. Then the equality

$$\delta(g \circ f) = \delta(f)(\delta(g) \circ f)$$

holds. $\square$

8.4. $p$-adic Cell Decomposition. — Cells are defined by induction on the number of variables:

8.4.1. Definition. — A $L$-cell $A \subset K$ is a (nonempty) set of the form

$$(8.4.1) \quad \{ t \in K \mid |\alpha|_1 |t - c|_2 |\beta|, \ t - c \in \lambda P_n \},$$

with constants $n > 0$, $\lambda, c$ in $K$, $\alpha, \beta$ in $K^\times$, and $\square_i$ either $<$ or no condition. A $L$-cell $A \subset K^{m+1}$, $m \geq 0$, is a set of the form

$$(8.4.2) \quad \{ (x, t) \in K^{m+1} \mid x \in D, \ |\alpha(x)|_1 |t - c(x)|_2 |\beta(x)|, \ t - c(x) \in \lambda P_n \},$$

with $(x, t) = (x_1, \ldots, x_m, t)$, $n > 0$, $\lambda$ in $K$, $D = \pi_m(A)$ a cell where $\pi_m$ is the projection $K^{m+1} \to K^m$, $L$-definable functions $\alpha, \beta : K^m \to K^\times$ and $c : K^m \to K$, and $\square_i$ either $<$ or no condition, such that the functions $\alpha, \beta$, and $c$ are analytic on $D$. We call $c$ the center of the cell $A$ and $\lambda P_n$ the coset of $A$. In either case, if $\lambda = 0$ we call $A$ a 0-cell and if $\lambda \neq 0$ we call $A$ a 1-cell.

In the $p$-adic semialgebraic case, Cell Decomposition Theorems are due to Cohen [11] and Denef [13], [15] and they were extended in [4] to the subanalytic setting where one can find the following version:

8.4.2. Theorem ($p$-adic Cell Decomposition). — Let $X \subset K^{m+1}$ and $f_j : X \to K$ be $L$-definable for $j = 1, \ldots, r$. Then there exists a finite partition of $X$ into $L$-cells $A_i$ with center $c_i$ and coset $\lambda_i P_n$ such that

$$|f_j(x, t)| = |h_{ij}(x)| \cdot |(t - c_i(x))^{a_{ij}} \lambda_i^{-a_{ij}}|_n^{1/n}, \quad \text{for each } (x, t) \in A_i,$$
with \((x,t) = (x_1, \ldots, x_m, t)\), integers \(a_{ij}\), and \(h_{ij} : K^m \to K\) \(\mathcal{L}\)-definable functions which are analytic on \(\pi_m(A_i), j = 1, \ldots, r\). If \(\lambda_i = 0\), we use the convention that \(a_{ij} = 0\).

We shall also use the following lemma from [5]:

**8.4.3. Lemma.** — Let \(X \subset K^{m+1}\) be \(\mathcal{L}\)-definable and let \(G_j\) be functions in \(C(X)\) in the variables \((x_1, \ldots, x_m, t)\) for \(j = 1, \ldots, r\). Then there exists a finite partition of \(X\) into \(\mathcal{L}\)-cells \(A_i\) with center \(c_i\) and coset \(\lambda_i P_n\), such that each restriction \(G_j|_{A_i}\) is a finite sum of functions of the form

\[
|(t - c_i(x))^a \lambda^{-a} \mid \pi_m(t - c_i(x))^s h(x),
\]

where \(h\) is in \(C(K^m)\), and \(s \geq 0\) and \(a\) are integers.

**8.5. Integration.** — By \(\text{Def}(\mathcal{L})\) we denote the category of \(\mathcal{L}\)-definable subsets \(X \subset K^n\) for \(n > 0\), with \(\mathcal{L}\)-definable maps as morphisms. We can now state a general integration result which states unicity and existence of a certain integral operator. This integral operator is introduced as a push-forward operator of functions under \(\mathcal{L}\)-definable maps, inspired by integration in the fibers with a measure on the fibers coming from Leray-differential forms.

In [16], see also [13], Denef proved stability of \(p\)-adic constructible functions under integration with respect to parameters in the semialgebraic case. Denef’s result had a major influence on our work [8] and the present one. It has been later generalized to the subanalytic case by the first author in [4] and [5].

**8.5.1. Proposition ([16, 4, 5]).** — Let \(W\) be a definable subset of \(K^n\) of dimension \(r\).

1. Let \(\varphi\) be in \(C(W \times K^m)\). Assume for every \(x\) in \(W\) the function \(t \mapsto \varphi(x,t)\) is integrable on \(K^m\). Then the function

\[
g(x) := \int_{K^m} \varphi(x,t)|dt|
\]

lies in \(C(W)\).

2. Let \(\varphi\) be in \(IC^{r+m}(W \times K^m)\). Then, there exists a function \(g\) in \(C(K^n)\) such that for all \(x\) in \(W \setminus Z\), with \(Z\) a \(\mathcal{L}\)-definable set of dimension \(< r\) in \(K^n\), one has

\[
g(x) = \int_{K^m} \varphi(x,t)|dt|.
\]

*Proof.* When \(W = K^n\), statement (1) is proved in [16] in the semialgebraic case and in [4] in the subanalytic case and statement (2) is proved in [5]. The proofs carry over literally to general \(W\). \(\Box\)

**8.5.2. Remark.** — The point in (2) is that it is possible that the set of points in \(W\) such that the restriction of \(\varphi\) to the fibers over which it is integrable may not be definable.
We shall now prove the following analogue of Theorem 10.1.1 of [8]. Note that the proof will be much easier, since integrable functions are already defined and Proposition 8.5.1 is available.

**8.5.3. Theorem.** — There exists a unique functor from $\text{Def}(\mathcal{L})$ to the category of groups sending a $\mathcal{L}$-definable set $X$ to the group $\text{IC}(X)$ such that a morphism $f : X \to Y$ in $\text{Def}(\mathcal{L})$ is sent to a group morphism $f_! : \text{IC}(X) \to \text{IC}(Y)$ satisfying the following axioms

(A1) Disjoint union: Assume that $X$, resp. $Y$, is the disjoint union of two $\mathcal{L}$-definable sets $X_1$ and $X_2$, resp. $Y_1$ and $Y_2$, such that $f(X_i) \subseteq Y_i$. Write $f_i : X_i \to Y_i$ for the restrictions. Then we have $f_! = f_!^1 \oplus f_!^2$ under the isomorphisms $\text{IC}(X) \simeq \text{IC}(X_1) \oplus \text{IC}(X_2)$ and $\text{IC}(Y) \simeq \text{IC}(Y_1) \oplus \text{IC}(Y_2)$.

(A2) Projection formula: For every $\alpha$ in $\mathcal{C}(Y)$ and $\beta$ in $\text{IC}(X)$, if $(\alpha \circ f)\beta$ is in $\text{IC}(X)$, then $f_!(\alpha \circ f)\beta = \alpha f_!(\beta)$.

(A3) Projection for 1-cells: Let $X \subseteq K^{n+1}$ be a 1-cell of dimension $r$ and $Y$ its image under the projection on $K^n$, $f : X \to Y$ the projection. Let $\varphi$ be a $\mu^r$-integrable function in $\mathcal{C}(X)$. By Proposition 8.5.1 there exists a $\mathcal{L}$-definable set $Z \subseteq Y$ such that $Y \setminus Z$ has dimension $< r - 1$ and such that the the function $g : Y \to \mathbb{Q} : y \mapsto \int_{f^{-1}(y)} 1_{Y \setminus Z}(y)\varphi(y, t)|dt|$ lies in $\mathcal{C}^{\leq r-1}(Y)$. We let $f_!([\varphi])$ be the class of $g$ in $\text{IC}^{r-1}(Y)$.

(A4) Projection for 0-cells: Let $X \subseteq K^{n+1}$ be a 0-cell of dimension $r$ and $Y$ its image under the projection on $K^n$, $f : X \to Y$ the projection. Then, we define $f_!(1_X)$ as $((|\text{Jac}f|) \circ f^{-1})^{-1}1_Y$ in $\text{IC}^r(Y)$, where $|\text{Jac}f|$ is as in 8.3.

**Proof.** — We will freely use classical forms of the change of variables formula, without mentioning it. Let us first check unicity. Since, by the graph construction, any morphism $f : X \to Y$ is the composition of the graph injection $i_f : X \to X \times Y$ and the projection $p : X \times Y \to Y$, it is enough, by functoriality, to prove unicity for $i_f$ and $p_i$. For projections $X \times Y \to Y$, one can assume $X = K^m$ and $Y = K^n$ by (A1). By induction on $m$, it is enough to define $p_i$ when $m = 1$. Consider $\varphi$ in $\mathcal{C}^r(K^{n+1})$ and assume it is integrable. By cell decomposition and linearity we may assume the support of $\varphi$ is contained in a $Z$ cell of dimension $r$. If $Z$ is a 1-cell, $f_!([\varphi])$ is given by (A3). In case $Z$ is a 0-cell, we may assume by (A2) that $\varphi = 1_Z$, and then $f_!([\varphi])$ is given by (A4). Finally, since $q \circ i_f = \text{id}_X$, with $q$ the projection $X \times Y \to X$, and since $q$ induces a bijection between the graph of $f$ and $X$, unicity for $i_f$ reduces to that of $q_!$ (an essentially similar argument is given with full details in the uniqueness section of the proof of Theorem 10.1.1 of [8]).

Let us now define $f_!$ for projections. Let $X$ be a definable subset of $Y \times K^n$ for $Y$ a definable subset of $K^m$ and consider the morphism $f : X \to Y$ induced by projection. Assume first that $X$ is of dimension $r$, $Y$ of dimension $s$, $f$ is surjective and all fibers of $f$ have dimension $r - s$. 

Let $\varphi$ be a $\mu^r$-integrable function in $C(X)$. There exists a definable subset $Z$ of $Y$, with dimension $< s$, such that the function

\[ g : y \mapsto \int_{f^{-1}(y)} 1_{Y \setminus Z} \delta \varphi \mu^{r-s} \]

lies in $C(Y)$, with $\delta$ as in section 8.3.2 and $\mu^{r-s}$ the measure as in section 8.2. Indeed, by Fubini and induction, and possibly after considering a partition of $X$ and $Y$, we may assume $n = 1$. Then, we may by cell decomposition assume $X$ is a cell. If $X$ is a 0-cell the statement is clear, if $X$ is a 1-cell the statement follows from Proposition 8.5.1. We may then define $f$ by Fubini and induction, and possibly after considering a partition of $X$ a 0-cell the statement is clear, if $X$ is a 1-cell the statement follows from Proposition 8.5.1. We may then define $f_i([\varphi])$ to be the class of $g$ in $C^{r-s}(Y)$. It follows from Fubini that $f_i([\varphi])$ lies in $IC^{r-s}(Y)$. Note that certainly (A3) and (A4) hold. Also, there is a unique way to extend that construction to a morphism $f_1 : IC(X) \to IC(Y)$ satisfying (A1) and (A2) for every morphism $f : X \to Y$ induced by a projection $Y \times K^m \to Y$. Indeed, it is enough to construct $f_1$ on $IC(X)$ and after cutting $X$ and $Y$ into finitely many definable pieces, one may assume the above condition is verified. Furthermore, by Lemma 8.3.3 $(g \circ f)_! = g_! \circ f_!$ for composable morphisms induced by projections.

Let us now define $i_1$ when $i : X \to Y$ is a definable injection. Let $\varphi$ be in $C^e(X)$. Consider a definable subset $X'$ of dimension $e$ of $X$ such that the support of a representative $\tilde{\varphi}$ of $\varphi$ is contained in $X'$. Denote by $\lambda : i(X') \to X'$ the inverse of the isomorphism induced by $i$. We define $i_1(\varphi)$ as the image of $[(\tilde{\varphi} \circ \lambda)]_e \text{Jac}(\lambda)$ in $C^e(Y)$ under the inclusion $C^e(i(X')) \to C^e(Y)$. Certainly $i_1(\varphi)$ is integrable if $\varphi$ is, hence we deduce a morphism $\lambda : IC(X) \to IC(Y)$.

For a general morphism $f : X \to Y$ one considers the factorisation $f = \pi_f \circ i_f$, with $i_f : X \to X \times Y$ the inclusion of the graph and $\pi_f : X \times Y \to Y$ the projection, and one sets $f_! := \pi_{f_!} \circ i_{f_!}$. One is then left with checking that the construction coincides with the previous one for injections and projections and that $(g \circ f)_! = g_! \circ f_!$ for composable morphisms. This is purely formal and performed exactly as the proof of the corresponding statements in the proof of Theorem 10.1.1 and Proposition 12.1.2 of 8.

8.6. Exponential constructible functions. — Fix an additive character $\psi : K \to \mathbb{C}^\times$ which is trivial on the maximal ideal $M$ of $R$ and such that $\psi(x) \neq 1$ for some $x$ in $K$ with $\text{ord}(x) = 0$.

For $X$ a $\mathcal{L}$-definable set, we let $C(X)_{\text{exp}}$ be the $\mathbb{Q}$-algebra generated by $C(X)$ and all functions $\psi(f)$, where $f : X \to K$ is $\mathcal{L}$-definable (cf. footnote 8.4).

Similarly, for each $d \geq 0$ we define $C^{\leq d}(X)_{\text{exp}}$ as the $\mathbb{Q}$-algebra generated by $C^{\leq d}(X)$ and all functions $\psi(f)$ with $f : X \to K$ $\mathcal{L}$-definable.

We set

\[ C(X)_{\text{exp}} = \bigoplus_d C^d(X)_{\text{exp}} \]

with

\[ C^d(X)_{\text{exp}} := C^{\leq d}(X)_{\text{exp}}/C^{\leq d-1}(X)_{\text{exp}}. \]
We call elements of $C(Z)^{\exp}$ constructible exponential Functions.

For $d \geq 0$ we define the group $IC^d(X)^{\exp}$ of integrable constructible exponential Functions as the $\mathbb{Q}$-algebra of functions which are defined almost everywhere, generated by $IC(X)$ and all functions $\psi(f)$ with $f : X \to K$ $\mathcal{L}$-definable. It is a graded subgroup of $C(Z)^{\exp}$ and a module over $C(Z)^{\exp}$.

The following exponential analogue of Proposition 8.5.1 is our main $p$-adic result:

8.6.1. Proposition. — Let $W$ be a definable subset of $K^n$ of dimension $r$.

(1) Let $\varphi$ be in $C(W \times K^m)^{\exp}$. Assume for every $x$ in $W$ the function $t \mapsto \varphi(x, t)$ is integrable on $K^m$. Then the function

$$g(x) := \int_{K^m} \varphi(x, t)|dt|$$

lies in $C(W)^{\exp}$.

(2) Let $\varphi$ be in $IC^{r+m}(W \times K^m)^{\exp}$. Then, there exists a function $g$ in $C(K^n)^{\exp}$ such that for all $x$ in $W \setminus Z$, with $Z$ a $\mathcal{L}$-definable set of dimension $< r$ in $K^n$, one has

$$g(x) = \int_{K^m} \varphi(x, t)|dt|.$$

Proof. — (1) follows easily from (2), so let us prove (2). By Fubini Theorem it is enough to consider the case $m = 1$. By linearity of the integral operator it is enough to prove the Proposition when $\varphi = \varphi_0 \psi(f)$ with $\varphi_0$ in $IC^{r+1}(W \times K)$ and $f : W \times K \to K$ a $\mathcal{L}$-definable morphism.

We partition $W \times K$ into $\mathcal{L}$-definable parts $B_1$, $B_2$, and $B_3$:

$$B_1 := \{(x, t) \in W \times K \mid f(x, t) \text{ is } C^1 \text{ at } t \text{ and } \frac{\partial f}{\partial t}(x, t) \neq 0\},$$

$$B_2 := \{(x, t) \in W \times K \mid f(x, t) \text{ is not } C^1 \text{ at } t\},$$

$$B_3 := \{(x, t) \in W \times K \mid f(x, t) \text{ is } C^1 \text{ at } t \text{ and } \frac{\partial f}{\partial t}(x, t) = 0\},$$

where $C^1$ at a point means continuously differentiable in an open neighborhood and $f(x, \cdot)$ denotes the function $K \to K : t \mapsto f(x, t)$ for each $x$ in $W$.

We can partition $B_2$ into finitely $\mathcal{L}$-definable sets $B_{2i}$ such that $f(x, t) = g_i(x)$ for each $i$ and for each $(x, t)$ in $B_{2i}$ for some $\mathcal{L}$-definable functions $g_i : W \to K$. This follows from the fact that for each $x$ in $W$ the set $B_{2x} := \{t \in K \mid (x, t) \in B_2\}$ is finite and uniformly bounded in number when $x$ varies, and from the $\mathcal{L}$-definability of choice functions, that is, there exist $\mathcal{L}$-definable sections of $\mathcal{L}$-definable maps (these statements follow immediately from cell decomposition 8.4.2, cf. also [17] and [19]).

Similarly, we can partition $B_3$ into finitely many $\mathcal{L}$-definable sets $B_{3i}$ such that $f(x, t) = r_i(x)$ for each $i$ and for each $(x, t)$ in $B_{3i}$ for some $\mathcal{L}$-definable functions $r_i : W \to K$. This follows from the facts that for each $x$ the image of the function $t \mapsto f(x, t)$ is discrete, hence finite and uniformly bounded when $x$ varies, and
from the \(L\)-definability of choice functions (again these statements follow from cell decomposition \[8.4.2\] cf. also \[17\] and \[19\]).

Hence, for the functions \(1_{B_1}\varphi\) with \(\ell = 2, 3\) the Proposition follows. By linearity of the integral operator we only have to prove the Proposition for the function \(1_{B_1}\varphi\).

By the implicit function theorem, the set \(\{t \mid f(x, t) = z, (x, t) \in B_1\}\) is discrete for each \(x\) in \(W\) and \(z\) in \(K\), hence finite and uniformly bounded when \(x\) and \(z\) vary, by the cell decomposition \[8.4.2\] (or by \[17\], \[19\]). By the existence of \(L\)-definable choice functions, we can partition \(B_1\) into finitely many \(L\)-definable parts \(B_{1i}\) such that \(f(x, \cdot)\) is injective on \(B_{1ix}\) for each \(i\) and each \(x\), with \(B_{1ix} := \{t \in K \mid (x, t) \in B_{1i}\}\). Hence, we may as well suppose that \(f(x, \cdot)\) is injective on \(B_{1x} := \{t \in K \mid (x, t) \in B_1\}\) itself. Then, we let \(T\) be the transformation

\[
(8.6.3)
T : \begin{cases} B_1 &\mapsto T(B_1) \\ (x, t) &\mapsto (x, f(x, t)), \end{cases}
\]

and let \(|\text{Jac}T|\) be the Jacobian of \(T\) as in \[8.3\]. Writing \(T(B_1)_x\) for \(\{t \in K \mid (x, t) \in T(B_1)\}\), one has by the change of variables rule for each \(x\) in \(\pi_{B_1}(B_1)\)

\[
(8.6.4)
\int_{B_{1x}} \varphi_0(x, t)\psi(f(x, t))|dt| = \int_{T(B_1)_x} (|\text{Jac}T| \circ T^{-1}(x, y))^{-1} \varphi_0(T^{-1}(x, y))\psi(y)|dy|.
\]

Now apply Lemma \[8.4.3\] to the function

\[
(8.6.5)
\varphi_1 : \begin{cases} T(B_1) &\mapsto Q \\ (x, y) &\mapsto (|\text{Jac}T| \circ T^{-1}(x, y))^{-1} \varphi_0(T^{-1}(x, y)) \end{cases}
\]

with respect to the variable \(y\) to obtain a partition of \(T(B_1)\) into \(L\)-cells \(A\) with center \(c\) and coset \(\lambda P_m\) such that each \(\varphi_{1|A}\) is a finite sum of functions of the form

\[
(8.6.6)
H(x, y) = |(y - c(x))^{a}\lambda^{-a}|^{\frac{1}{m}}v(y - c(x))^sh(x),
\]

where \(h : W \to Q\) is in \(C(W)\), and \(s \geq 0\) and \(a\) are integers.

\[8.6.2.\] **Claim.** — Possibly after refining the partition, we can assure that for each \(A\) either the projection \(A' := \pi_{W}(A) \subset W\) has zero \(\mu^*\)-measure, or we can write \(\varphi_{1|A}\) as a sum of terms \(H\) of the form \[8.6.6\] such that \(H\) is \(\mu^*\)-integrable over \(A\) and \(H(x, \cdot)\) is integrable over \(A_x := \{y \mid (x, y) \in A\}\) for all \(x\) in \(A'\).

As this claim is very similar to Claim 2 of \[5\] we will only give an indication of its proof. Partitioning further, we may suppose that \(v(y - c(x))\) either takes only one value on \(A\) or infinitely many values. If \(v(y - c(x))\) only takes one value on \(A\), we may suppose that the exponents \(a\) and \(s\) as in \[8.6.6\] are zero. Now apply Lemma \[8.4.3\] to each \(h\) and to the norms of all the \(L\)-definable functions appearing in the description of the cells \(A\) in a similar way and do this inductively for each variable. This way, the claim is reduced to a summation problem over a Presburger set of integers, which is easily solved. This proves the claim.
Fix a cell $A$ and a term $H$ as in the claim. The cell $A$ has by definition the following form

$$A = \{(x,y) \mid x \in A', \; v(\alpha(x)) \square_1 v(y-c(x)) \square_2 v(\beta(x)), y-c(x) \in \lambda P_m\},$$

where $A' = \pi_W(A)$ is a cell, $\square_i$ is $< \text{or no condition}$, and $\alpha, \beta : W \to K^\times$ and $c : W \to K$ are $L$-definable functions. We focus on a cell $A$ of dimension $r+1$, in particular, $\lambda \neq 0$ and $A'$ is of dimension $r$.

For $x$ in $A'$, we denote by $I(x)$ the value

$$I(x) = \int_{y \in A_x} H(x,y) \psi(y) \, |dy|,$$

where $A_x = \{y \in K \mid (x,y) \in A\}$. Write

$$G(j) := \int_{v(u) = j, \; u \in \lambda P_m} \psi(u) \, |du|.$$  

(8.6.7)

We easily find

$$I(x) = \psi(c(x)) h(x) |\lambda|^{-a/m} \sum_{\square_2 (j) = \text{8.6.3}} q^{-ja/m} j^s G(j),$$

(8.6.8)

where the summation is over

$$(8.6.9) \quad J := \{j \mid v(\alpha(x)) \square_1 j \square_2 v(\beta(x)), \; j \equiv v(\lambda) \mod m\}.$$

By Hensel’s Lemma, there exists an integer $e \geq 0$ such that all units $u$ with $u \equiv 1 \mod \pi_0^e$ are $m$-th powers (here, $\pi_0$ is such that $v(\pi_0) = 1$). Hence, $G(j)$ is zero whenever $j \leq -e$ (since in this case one essentially sums a nontrivial character over a finite group). Also, when $j > 0$ then $G(j) = \int_{v(u) = j, \; u \in \lambda P_m} |du|$, which is independent of $\psi$. We find that $I(y)$ is equal to

$$\psi(c(y)) h(y) |\lambda|^{-a/m} \left( \sum_{-e \leq j \leq 0} q^{-ja/m} j^s G(j) + \sum_{0 \leq j} q^{-ja/m} j^s G(j) \right).$$

(8.6.10)

The factors of (8.6.10) before the brackets clearly are in $C(W)^{\text{exp}}$. The (parameterized) finite sum inside the brackets of (8.6.10) can be written as a finite sum of generators of $C(W)^{\text{exp}}$ since each $G(j) = p^{-j} \alpha_{j \mod e+n}$ with each $\alpha_{j \mod e+n}$ some $\mathbb{Q}$-linear combination of values of $\psi$ which only depends on $j \mod e+n$, and hence, it is also in $C(W)^{\text{exp}}$. The infinite sum inside the brackets of (8.6.10) is in $C(W)$ by Proposition 8.5.1 and the above discussion. This finishes the proof of the Proposition. 

One may extend Theorem 8.5.3 to the exponential setting as follows:

8.6.3. Theorem. — There exists a unique functor from Def($L$) to the category of groups sending a $L$-definable set $X$ to the group $IC(X)^{\text{exp}}$ such that a morphism $f : X \to Y$ in Def($L$) is sent to a group morphism $f_1 : IC(X)^{\text{exp}} \to IC(Y)^{\text{exp}}$ satisfying the following axioms
(A1) Compatibility: For every morphism \( f : X \to Y \) in \( \text{Def}(\mathcal{L}) \), the map \( f_! : \text{IC}(X)^{\exp} \to \text{IC}(Y)^{\exp} \) is compatible with the inclusions of groups \( \text{IC}(X) \to \text{IC}(X)^{\exp} \) and \( \text{IC}(Y) \to \text{IC}(Y)^{\exp} \) and with the map \( f_! : \text{IC}(X) \to \text{IC}(Y) \) as constructed in Theorem 8.5.3.

(A2) Disjoint union: Assume that \( X, \text{ resp. } Y \), is the disjoint union of two \( \mathcal{L} \)-definable sets \( X_1 \) and \( X_2 \), resp. \( Y_1 \) and \( Y_2 \), such that \( f(X_i) \subset Y_i \). Write \( f_i : X_i \to Y_i \) for the restrictions. Then we have \( f_! = f_1! \oplus f_2! \) under the isomorphisms \( \text{IC}(X)^{\exp} \cong \text{IC}(X_1)^{\exp} \oplus \text{IC}(X_2)^{\exp} \) and \( \text{IC}(Y)^{\exp} \cong \text{IC}(Y_1)^{\exp} \oplus \text{IC}(Y_2)^{\exp} \).

(A3) Projection formula: For every \( \alpha \) in \( \mathcal{C}(Y)^{\exp} \) and \( \beta \) in \( \text{IC}(X)^{\exp} \), if \( (\alpha \circ f)\beta \) is in \( \text{IC}(X)^{\exp} \), then \( f_!( (\alpha \circ f) \beta ) = \alpha f_!( \beta ) \).

(A4) Projection for 1-cells: Let \( X \subset K^{n+1} \) be a 1-cell of dimension \( r \) and \( Y \) its image under the projection to \( K^n \), \( f : X \to Y \) the projection. Let \( \varphi \) be a \( \mu^r \)-integrable function in \( \mathcal{C}(X)^{\exp} \). By Proposition 8.6.1 there exists a \( \mathcal{L} \)-definable set \( Z \subset Y \) such that \( Y \setminus Z \) has dimension \( < r - 1 \) and such that the function \( g : Y \to \mathbb{Q} : y \mapsto \int_{\bar{y}^{-1}(y)} 1_{Y \setminus Z}(y) \varphi(y,t) \, dt \) lies in \( \mathcal{C}^{\leq r-1}(Y)^{\exp} \). We let \( f_!( [\varphi]_r ) \) be the class of \( g \) in \( \text{IC}^{\leq r-1}(Y)^{\exp} \).

Proof. — The proof is quite formal and similar to proofs we have already given. Indeed, uniqueness is proven along similar lines than those given in 6.3, and for existence one can proceed similarly as in the proof of Theorem 8.5.3 using Proposition 8.6.1 instead of Proposition 8.5.1.

8.7. Variants: adding sorts and relative versions. — By analogy with the motivic framework, we now expand the language \( \mathcal{L} \) to a three sorted language \( \mathcal{L}' \) having \( \mathcal{L} \) as language for the valued field sort, the ring language \( \mathbb{L}_{\text{Rings}} \) for the residue field, and the Presburger language \( \mathbb{L}_{\text{PR}} \) for the value group together with maps \( \text{ord} \) and \( \text{ac} \) as in 2.1. By taking the product of the measure \( \mu^m \) with the counting measure on \( k_K^n \times \mathbb{Z}^r \) one defines a measure still denoted by \( \mu^m \) on \( K^m \times k_K^n \times \mathbb{Z}^r \).

One defines the dimension of a \( \mathcal{L}' \)-definable subset \( X \) of \( K^m \times k_K^n \times \mathbb{Z}^r \) as the dimension of its projection \( \pi(X) \subset K^m \). If \( X \) is of dimension \( d \), one defines a measure \( \mu^d \) on \( X \) extending the previous construction on \( X \) by setting

\[
\mu^d(W) := \int_{\pi(X)} \pi_!(1_W) \mu^d
\]

with \( \pi_!(1_W) \) the function \( y \mapsto \text{card}(\pi^{-1}(y) \cap W) \).

For such an \( X \), one defines \( \mathcal{C}(X) \) as the \( \mathbb{Q} \)-algebra of functions on \( X \) generated by functions \( \alpha \) and \( p^{-\alpha} \) with \( \alpha : X \to \mathbb{Z} \) definable in \( \mathcal{L}' \). Note that this definition coincides with the previous one when \( n = r = 0 \). Since \( \mathcal{L}' \) is interpretable in \( \mathcal{L} \), the formalism developed in this section extends to \( \mathcal{L}' \)-definable objects in natural way. In particular the definitions of \( \mathcal{C}^{\leq d} \), \( C^d \), IC, \( |\text{Jac}| \), \( \delta \), \( \mathcal{C}^{\exp} \), etc, extend readily to \( \mathcal{L}' \)-definable objects and we have:

8.7.1. Theorem. — (1) The statement of Theorem 8.5.3 extends to \( \text{Def}(\mathcal{L}') \) after adding the additional axiom:
(A5) Let \( \pi: X \times k^n_K \times \mathbb{Z}^r \to X \) be the projection with \( X \) in \( \text{Def}(\mathcal{L}') \). For any \( \varphi \) in \( \text{IC}(X \times k^n_K \times \mathbb{Z}^r) \) and every \( x \) in \( X \),

\[
\pi_1(\varphi)(x) = \sum_{\pi(y) = x} \varphi(y).
\]

(2) The statement of Theorem 8.6.3 extends to \( \text{Def}(\mathcal{L}') \).

8.7.2. — Fix \( \Lambda \) in \( \text{Def}(\mathcal{L}') \). We consider the category \( \text{Def}_\Lambda(\mathcal{L}') \) whose objects are \( \mathcal{L}' \)-definable morphisms \( f: S \to \Lambda \), a morphism \( g: (f: S \to \Lambda) \to (f': S' \to \Lambda) \) being a morphism \( g: S \to S' \) in \( \text{Def}(\mathcal{L}') \) with \( f' \circ g = f \). For \( f: S \to \Lambda \) in \( \text{Def}_\Lambda(\mathcal{L}') \) we define the relative dimension of \( S \) over \( \Lambda \) as the maximum of the dimension of the fibers of \( f \). For \( d \) in \( \mathbb{Z} \), define \( C^{\leq d}(S \to \Lambda) \) as the ideal of \( \mathcal{C}(S) \) generated by the characteristic functions of \( \mathcal{L}' \)-definable subsets of \( S \) of relative dimension \( \leq d \) over \( \Lambda \). Set

\[
C^d(S \to \Lambda) := C^{\leq d}(S \to \Lambda)/C^{\leq d-1}(S \to \Lambda),
\]

and define the graded group

\[
C(S \to \Lambda) := \oplus_d C^d(S \to \Lambda).
\]

For every \( \lambda \) in \( \Lambda \) there exists a graded group homomorphism called restriction to \( \lambda \)

\[
|f^{-1}(\lambda)|: C(S \to \Lambda) \to C(f^{-1}(\lambda)),
\]

sending \( \varphi \) in \( C(S \to \Lambda) \) to its restriction to the fiber \( f^{-1}(\lambda) \).

We define \( \text{IC}(S \to \Lambda) \) as the graded subgroup of \( C(S \to \Lambda) \) consisting of \( \varphi \in C(S \to \Lambda) \) such that, for every \( \lambda \) in \( \Lambda \), the restriction \( \varphi|_{f^{-1}(\lambda)} \) lies in \( \text{IC}(f^{-1}(\lambda)) \).

One defines similarly \( C^{\leq d}(S \to \Lambda)^{\exp}, C(S \to \Lambda)^{\exp}, \text{IC}(S \to \Lambda)^{\exp} \) and

\[
|f^{-1}(\lambda)|: C(S \to \Lambda)^{\exp} \to C(f^{-1}(\lambda))^{\exp}.
\]

If \( g: S \to S' \) is an isomorphism in \( \text{Def}_\Lambda(\mathcal{L}') \) between subsets of relative dimension \( d \), on denotes by \( |\text{Jac}_\Lambda g| \) the function in \( C^d(S \to \Lambda) \) such that

\[
|\text{Jac}_\Lambda g|_{|f^{-1}(\lambda)} = |\text{Jac}(g|_{f^{-1}(\lambda)})|
\]

for every \( \lambda \) in \( \Lambda \).

8.7.3. Proposition. — For \( g: S \to S' \) a morphism in \( \text{Def}_\Lambda(\mathcal{L}') \), there exists a unique morphism

\[
g_\Lambda: \text{IC}(S \to \Lambda) \to \text{IC}(S' \to \Lambda)
\]

which sends \( \varphi \in \text{IC}(S \to \Lambda) \) to the unique \( \psi \in \text{IC}(S' \to \Lambda) \) such that for each \( \lambda \in \Lambda \)

\[
(g|_{S_\lambda})(\varphi|_{f^{-1}(\lambda)}) = \psi|_{S'_\lambda},
\]

with \( S_\lambda \) and \( S'_\lambda \) the fibers and \( (g|_{S_\lambda})! \) the direct image as constructed above, and similarly a morphism

\[
g_\Lambda: \text{IC}(S \to \Lambda)^{\exp} \to \text{IC}(S' \to \Lambda)^{\exp}.
\]
Furthermore, these morphisms \( g_\Lambda \) satisfy the relative analogues of properties (A1)-(A4) of Theorem 8.5.3, (A1)-(A4) of Theorem 8.6.3, and (A5) of Theorem 8.7.1 respectively, where in (A4) of Theorem 8.5.3, \( |JC| \) is replaced by its relative analogue \( |JC_\Lambda| \).

Proof. — One can either remark that the proofs of Theorem 8.5.3, Theorem 8.6.3 and Theorem 8.7.1 carry over literally to the relative case, or deduce it from the absolute case using Proposition 8.5.1 and Proposition 8.6.1.

Since \( IC(\Lambda \to \Lambda) = C(\Lambda) \), when \( g \) is the morphism \( S \to \Lambda \), one gets from (8.7.7) a morphism

\[
\mu_\Lambda : IC(S \to \Lambda) \to C(\Lambda).
\]

9. Specialization and transfer

In this section we obtain new results on specialization to \( p \)-adic and \( \mathbb{F}_q((t)) \)-integration and a transfer principle for exponential integrals with parameters from \( \mathbb{Q}_p \) and from \( \mathbb{F}_q((t)) \). Some of the results which are announced in [9] are generalized here to exponential constructible functions. The specialization principle given here generalizes the one of [18].

9.1. Specialization to valued local fields. —

9.1.1. Notation. — Let \( k \) be a number field with ring of integers \( \mathcal{O} \). We denote by \( \mathcal{A}_\mathcal{O} \) the collection of all the \( p \)-adic completions of \( k \) and all finite field extensions of \( k \). We denote by \( \mathcal{B}_\mathcal{O} \) the set of all local fields of positive characteristic over \( \mathcal{O} \), that is, endowed with an \( \mathcal{O} \)-algebra structure. For \( N > 0 \), denote by \( \mathcal{C}_{\mathcal{O},N} \) the collection of \( K \) in \( \mathcal{A}_\mathcal{O} \cup \mathcal{B}_\mathcal{O} \) with \( \text{char} K > N \) and write \( \mathcal{C}_\mathcal{O} \) for \( \mathcal{C}_{\mathcal{O},1} \). By \( \mathcal{A}_{\mathcal{O},N} \), resp. \( \mathcal{B}_{\mathcal{O},N} \), denote \( \mathcal{C}_{\mathcal{O},N} \cap \mathcal{A}_\mathcal{O} \), resp. \( \mathcal{C}_{\mathcal{O},N} \cap \mathcal{B}_\mathcal{O} \).

For \( K \) in \( \mathcal{C}_\mathcal{O} \), we write \( R_K \) for its valuation ring, \( M_K \) for the maximal ideal, \( k_K \) for its residue field, and \( q(K) \) for the number of elements of \( k_K \). For each choice of a uniformizer \( \varpi_K \) of \( R_K \), there is a unique multiplicative map \( \varpi_K : K^\times \to k_K^\times \) which extends the projection \( R_K^\times \to k_K^\times \) and sends \( \varpi_K \) to 1, and we extend this by setting \( \varpi_K(0) = 0 \). We denote by \( \mathcal{D}_K \) the collection of additive characters \( \psi : K \to \mathbb{C}^\times \) such that

\[
\psi(x) = \exp((2\pi i/p)\text{Tr}_{k_K}(\bar{x}))
\]

for \( x \in R_K \), with \( p \) the characteristic of \( k_K \), \( \text{Tr}_{k_K} \) the trace of \( k_K \) over its prime subfield and \( \bar{x} \) the natural projection modulo \( M_K \) of \( x \) into \( k_K \).

9.1.2. Interpretation of functions. — As a language that can be interpreted in all the fields of \( \mathcal{C}_\mathcal{O} \), we shall use \( \mathcal{L}_\mathcal{O} := \mathcal{L}_{\mathcal{D},p}(\mathcal{O}[t]) \), that is, the language \( \mathcal{L}_{\mathcal{D},p} \) with coefficients in \( k \) for the residue field sort and coefficients in \( \mathcal{O}[t] \) for the valued field sort. (Instead of \( \mathcal{O}[t] \), any subring of \( \mathcal{O}[t] \) containing \( \mathcal{O}[t] \) can be used as coefficients.) To say that a definable subassignment is defined in the language \( \mathcal{L}_\mathcal{O} \),
we say that it belongs to $\text{Def}(\mathcal{L}_O)$, and for a constructible function we say likewise that it belongs to $\mathcal{C}(S, \mathcal{L}_O)$, $\mathcal{C}(S, \mathcal{L}_O)^{\exp}$, and so on, when it is defined in $\mathcal{L}_O$.

For every uniformizer $\varpi_K$ of $R_K$, one may consider $K$ as an $\mathcal{O}[t]$-algebra via the morphism

$$(9.1.1) \quad \lambda_{O,K} : \mathcal{O}[t] \to K : \sum_{i \in \mathbb{N}} a_i t^i \mapsto \sum_{i \in \mathbb{N}} a_i \varpi_K^i.$$ 

Hence, if one interprets elements $a$ of $\mathcal{O}[t]$ as $\lambda_{O,K}(a)$, an $\mathcal{O}[t]$-formula $\varphi$ defines for all $K$ in $\mathcal{C}_O$ a definable subset $\varphi_K$ of $K^m \times k_K^n \times \mathbb{Z}^r$ for some $m, n, r$, for every choice of uniformizer $\varpi_K$ of $R_K$.

On the other hand, the formula $\varphi$ gives rise to a definable subassignment $X$ of $h[m, n, r]$ and if $\varphi'$ gives rise to the same subassignment $X$ then $\varphi_K = \varphi'_K$ for all $K$ in $\mathcal{C}_{O,N}$ for some large enough $N$, independently of the choice of uniformizer.\(^{(2)}\)

With a slight abuse of notation, for $X$ a definable subassignment of $h[m, n, r]$ in $\text{Def}(\mathcal{L}_O)$, we write $X_K$ for the subassignment defined by $\varphi_K$ where $\varphi$ is a $\text{Def}(\mathcal{L}_O)$-formula defining $X$, which is well determined for $K$ in $\mathcal{C}_{O,N}$ for some large enough $N$, as explained above. Similarly, if $f : X \to Y$ is a $\mathcal{L}_O$-definable morphism, we obtain a function $f_K : X_K \to Y_K$ for all $K$ in $\mathcal{C}_{O,N}$ for some $N$.

With a similar abuse of notation, we can interpret a function $\varphi$ in $\mathcal{C}(X, \mathcal{L}_O)$ as a function $X_K \to \mathbb{Q}$, for $N$ large enough and $K$ in $\mathcal{C}_{O,N}$, as follows.

First suppose that $\varphi$ is in $K_0(\text{RDef}_X(\mathcal{L}_O))$ and of the form $[\pi : W \to X]$ for some $\mathcal{L}_O$-definable subassignment $W$ in $\text{RDef}_X(\mathcal{L}_O)$. For $K$ in $\mathcal{C}_O$, consider $W_K$, which is a subset of $X_K \times (k_K)^\ell$ for some $\ell$, and consider the natural projection $\pi_K : W_K \to X_K$. Then one sets

$$(9.1.2) \quad \varphi_K : \begin{cases} X_K \to \mathbb{Q} \\ x \mapsto \text{card}\left(\pi_K^{-1}(x)\right) \end{cases}.$$ 

Similarly as before, this is well determined for $N$ large enough and $K$ in $\mathcal{C}_{O,N}$. By linearity that construction extends to $K_0(\text{RDef}_X(\mathcal{L}_O))$.

Let us now define $\varphi_K$ when $\varphi$ lies in $\mathcal{P}(X)$. If one expresses $\varphi$ in terms of $\mathcal{L}$ and of definable morphisms $\alpha : X \to \mathbb{Z}$, replacing $\mathcal{L}$ by $q_K$ and each $\alpha$ by $\alpha_K : X_K \to \mathbb{Z}$, one gets a function $\varphi_K : X_K \to \mathbb{Q}$ again well determined for $K$ in $\mathcal{C}_{O,N}$ when $N$ is large enough. By tensor product, this defines $\varphi_K$ for general $\varphi$ in $\mathcal{C}(X, \mathcal{L}_O)$.

Next we interpret $\varphi$ in $\mathcal{C}(X, \mathcal{L}_O)^{\exp}$ as a function $\varphi_{K,\psi_K} : X_K \to \mathbb{C}$, for $K$ in $\mathcal{C}_{O,N}$ when $N$ is large enough and for every $\psi_K$ in $\mathcal{D}_K$, as follows.

First suppose that $\varphi$ in $K_0(\text{RDef}_X(\mathcal{L}_O))^{\exp}$ is of the form $[W, g, \xi]$ with $W$ a $\mathcal{L}_O$-definable subassignment, where $g : W \to h[1,0,0]$ and $\xi : W \to h[0,1,0]$ are $\mathcal{L}_O$-definable morphisms. For $K$ in $\mathcal{C}_O$, consider $W_K$, $g_K : W_K \to K$, and $\xi_K : W_K \to k_K$,\(^{(2)}\)

\(^{(2)}\)This follows from either from Ax and Kochen \[11, 39\], Eršov \[21\], Cohen \[11\], Pas \[29\], or others, or from a small variant of Proposition 5.2.1 of \[18\] (a result of Ax-Kochen-Eršov type that uses ultraproducts and follows from the Theorem of Denef-Pas).
and consider the projection \( \pi : W_K \to X_K \). Then, for \( \psi_K \) in \( D_K \), one sets

\[
(9.1.3) \quad \varphi_{K, \psi_K} : X_K \to \mathbb{Q} \quad \text{by} \quad x \mapsto \sum_{y \in \pi^{-1}(x)} \psi_K(g_K(y)) \exp((2\pi i/p)\text{Tr}_{k_K}(\xi_K(y))).
\]

Similarly as before, this is well determined for \( N \) large enough and for all \( K \) in \( \mathcal{C}_{O,N} \) and all \( \psi_K \) in \( D_K \). The construction being compatible with the previous one, this defines \( \varphi_{K, \psi_K} \) for general \( \varphi \in \mathcal{C}(X, \mathcal{O})^\exp \), by tensor product.

9.1.3. Integration. — Let \( K \) be in \( \mathcal{C}_O \) and consider a - not necessarily definable - subset \( A \) of \( K^m \times k^n_K \times \mathbb{Z}^r \). Let \( A' \) be the image of \( A \) under the projection \( K^m \times k^n_K \times \mathbb{Z}^r \to K^m \) and define the dimension of \( A \) as the dimension of the Zariski closure of \( A' \) in \( A^n_K \) with \( \dim \emptyset := -1 \). Let \( f : A \to \Lambda \) be any function, with \( \Lambda \) a subset of \( K^m' \times k^{n'}_K \times \mathbb{Z}^{r'} \). The relative dimension of \( f \) is defined to be the maximum of the dimensions of the fibers; it is also called the relative dimension of \( A \) over \( \Lambda \).

For \( A \) and \( A' \) as above, we denote by \( \tilde{A} \) the Zariski closure of \( A' \) in \( A^n_K \). If \( \tilde{A} \) is of dimension \( d \), we consider the canonical \( d \)-dimensional measure \( \mu^d \) on \( \tilde{A}(K) \), cf. [30, 28], and put the counting measure on \( k^n_K \times \mathbb{Z}^r \). We shall still write \( \mu_\text{d} \) for the product measure on \( \tilde{A}(K) \times k^n_K \times \mathbb{Z}^r \), formed by taking the product of the above \( \mu_\text{d} \) with the counting measure, and we finally still denote by \( \mu^d \) its restriction to \( A \), similarly as in section 3.

We denote by \( \mathcal{F}(A) \) the algebra of all functions \( A \to \mathbb{C} \). and we say a function \( \varphi \) in \( \mathcal{F}(A) \) is integrable in dimension \( d \) if \( A \) and \( \varphi \) are measurable and \( \varphi \) is integrable with respect to the measure \( \mu^d \). More generally, we say that a function \( \varphi \in \mathcal{F}(A) \) is integrable in dimension \( e \) if the support \( B \) of \( \varphi \) is of dimension \( e \) and the restriction \( \varphi_{\mid B} \) is integrable in dimension \( e \) as defined above. For \( e \geq 0 \) an integer, we denote by \( \mathcal{F}^\leq_e(A) \) the ideal of \( \mathcal{F}(A) \) of functions with support of dimension \( \leq e \) and we set

\[
(9.1.4) \quad F^e(A) := \mathcal{F}^\leq_e(A)/\mathcal{F}^\leq_{e-1}(A) \quad \text{and} \quad F(A) := \oplus_e F^e(A).
\]

We define \( IF^e(A) \) as the subgroup of \( F^e(A) \) consisting of functions in \( F^e(A) \) which are integrable in dimension \( e \) and denote by \( \mu : IF^e(A) \to \mathbb{C} \) as the integration operator. We set \( IF(A) := \oplus e IF^e(A) \) and extend \( \mu \) to \( \mu : IF(A) \to \mathbb{C} \) by linearity.

Let \( f : A \to \Lambda \) be a mapping as before. Let \( \mathcal{F}^\leq_e(A \to \Lambda) \) be the ideal of \( \mathcal{F}(A) \) of functions with support of relative dimension \( \leq e \) over \( \Lambda \). The groups \( F^e(A \to \Lambda) \) and \( F(A \to \Lambda) \) are defined correspondingly. For every \( \lambda \) in \( \Lambda \), there is a natural restriction map, which is a graded group homomorphism,

\[
(9.1.5) \quad \mid_{f^{-1}(\lambda)} : F_K(A \to \Lambda) \to F_K(f^{-1}(\lambda)),
\]

defined by sending \( \varphi \) in \( F_K(A \to \Lambda) \) to the restriction of \( \varphi \) to the fiber \( f^{-1}(\lambda) \).

We define \( IF_K(A \to \Lambda) \) as the graded subgroup of \( F_K(A \to \Lambda) \) of Functions whose restrictions to all fibers lie in \( IF \), where restriction is as just defined, and we denote by \( \mu_\Lambda \) the unique mapping

\[
(9.1.6) \quad \mu_\Lambda : IF(A \to \Lambda) \to \mathcal{F}(\Lambda)
\]

such that \( \mu_\Lambda(\varphi)(\lambda) = \mu(\varphi_{\mid_{f^{-1}(\lambda)}}) \) for every \( \varphi \) in \( IF(A \to \Lambda) \) and every point \( \lambda \) in \( \Lambda \).
9.1.4. — We still have to go one step further in the interpretation of functions. Let \( f : S \to \Lambda \) be a morphism in \( \text{Def}(\mathcal{L}_\mathcal{O}) \). Let \( \varphi \) be in \( C(S \to \Lambda, \mathcal{L}_\mathcal{O})^{\text{exp}} \). The function \( \varphi \) is the class of a tuple \( (\varphi_d)_d \) with \( \varphi_d \) in \( C^{\leq d}(S \to \Lambda, \mathcal{L}_\mathcal{O})^{\text{exp}} \), where only finitely many components are non-zero. Then, for \( N > 0 \) large enough, \( K \in \mathcal{C}_{\mathcal{O}, N} \), and \( \psi_K \in \mathcal{D}_K \), each function \( \varphi_{d,K,\psi_K} \) lies in \( \mathcal{F}_{\leq d}^K(S_K) \), and by taking the class of \( (\varphi_{d,K,\psi_K})_d \), we get a function \( \varphi_{K,\psi_K} \) in \( \mathcal{F}_K(S_K \to \Lambda_K) \).

The following result says that the motivic exponential integral specializes to the corresponding integrals over the local fields of high enough residue field characteristic.

9.1.5. Theorem (Specialization Principle). — Let \( f : S \to \Lambda \) be a morphism in \( \text{Def}(\mathcal{L}_\mathcal{O}) \). Take \( \varphi \) in \( \mathcal{IC}(S \to \Lambda, \mathcal{L}_\mathcal{O})^{\text{exp}} \). Then there exists \( N > 0 \) such that for all \( K \) in \( \mathcal{C}_{\mathcal{O}, N} \), every choice of a uniformizer \( \varpi_K \) of \( R_K \), and all \( \psi_K \) in \( \mathcal{D}_K \), \( \varphi_{K,\psi_K} \) lies in \( \mathcal{IF}_K(S_K \to \Lambda_K) \) and

\[
(\mu_\mathcal{L}(\varphi))_{K,\psi_K} = \mu_{\Lambda_K}(\varphi_{K,\psi_K}).
\]

Proof. — Let us first consider the case where \( \varphi \) lies in \( \mathcal{IC}(S \to \Lambda, \mathcal{L}_\mathcal{O}) \). We can assume \( \varphi \) lies in \( \mathcal{IC}_+(S \to \Lambda, \mathcal{L}_\mathcal{O}) \), using notations from \( \mathcal{S} \). In \( \mathcal{S} \), the definition of relative integrability of \( \varphi \) and the value of the relative integral were defined simultaneously along the following lines. One may assume \( S \) is a definable subassignment of \( \Lambda[m, n, r] := \Lambda \times h[m, n, r] \) and, using cell decomposition and induction, it is enough, by Theorem 14.1.1 of \( \mathcal{S} \) to consider the behaviour of the integrability condition and the computation of the integral for: 1) projection along \( \mathbb{Z} \)-variables, 2) projection along residue field variables, 3) projections \( \Lambda[m, n, r] \to \Lambda[m - 1, n, r] \) when \( S \) is a 0-cell, 4) projections \( \Lambda[m, n, r] \to \Lambda[m - 1, n, r] \) when \( S \) is a 1-cell adapted to \( \varphi \). Note that certainly given \( \varphi \) the cell decompositions involved here will specialize to cell decomposition defined by the specialized conditions when \( N \) is large enough. This is a special instance of the compactness argument in model theory. In 1), one can assume \( \varphi \) is a Presburger function, that is lies in \( \mathcal{P}_+(S) \) with the notation of loc. cit. In that case, the integrability condition was built from the start to be compatible with specialization, since it was expressed by “summability when \( \mathbb{L} \) replaced by \( q > 1 \)”.

Also the relative integral was defined by summing up series in powers of \( \mathbb{L} \) and specializes to \( \mathbb{Z}^\ast \) with respect to the counting measure. Step 2) is tautologically compatible with specialization. In step 3) a function \( \mathbb{L}^{\text{ordjac}} \), defined almost everywhere occurs, and for \( N \) large enough it specializes to \( |\text{Jac}_f_K| \). By the change of variables formula for integrals over fields in \( \mathcal{C}_\mathcal{O} \), it follows that 3) is compatible with specialization. Finally step 4) is compatible with specialization since the relative motivic volume of a 1-cell \( Z \) specializes to the volume of the corresponding \( Z_K \), for \( N \) large enough, by definition.

When \( \varphi \) lies in \( \mathcal{C}(S, \mathcal{L}_\mathcal{O})^{\text{exp}} \), the statement about compatibility of relative integrability with specialization holds by the previous construction. The construction of the relative integral of \( \varphi \) can be performed along similar lines as before. Specialization for steps 1), 2) and 3) holds for the same reasons as before and only step 4) needs to be considered. It follows from our constructions than it is enough to show...
that the relative integral of the function $E(z)$ on a 1-cell with special coordinate $z$ specializes to the corresponding one over $K$, for $N$ large enough, which is clear by construction, cf. also Lemma 7.3.2.

For $p$-adic fields, we can say more, using the formalism of §7.4.

9.1.6. Theorem (Specialization Principle). — Let $\Lambda$ be in $\text{Def}(\mathcal{L}_O)$ and let $f : S \to S'$ be a morphism in $\text{Def}_\Lambda(\mathcal{L}_O)$. Let $\varphi$ be in $IC(S \to \Lambda, \mathcal{L}_O)^{\exp}$. Then there exists $N > 0$ such that for all $K$ in $\mathcal{A}_{O,N}$, each choice of a uniformizer $\varpi_K$ of $R_K$, and all $\psi_K$ in $\mathcal{D}_K$ the Function $\varphi_{K, \psi_K}$ lies in $IC(S_K \to \Lambda_K)^{\exp}$ and such that

$$(f!\varphi)(K, \psi_K) = f!\Lambda_K(\varphi_{K, \psi_K}).$$

Proof. — Similar to the proof of Theorem 9.1.5.

9.2. Transfer principle for integrals with parameters. — We start by proving the following abstract form of the Transfer principle:

9.2.1. Proposition. — Let $\varphi$ be in $\mathcal{C}(\Lambda, \mathcal{L}_O)^{\exp}$. Then, there exists an integer $N$ such that for all $K_1, K_2$ in $\mathcal{C}_{O,N}$ with $k_{K_1} \simeq k_{K_2}$ the following holds:

$$\varphi_{K_1, \psi_{K_1}} = 0 \text{ for all } \psi_{K_1} \in \mathcal{D}_{K_1}$$

if and only if

$$\varphi_{K_2, \psi_{K_2}} = 0 \text{ for all } \psi_{K_2} \in \mathcal{D}_{K_2}.$$

Proof. — We first consider the case when $\varphi$ lies in $\mathcal{C}(\Lambda, \mathcal{L}_O)^e$. Suppose that $\Lambda$ is a $\mathcal{L}_O$-definable subassignment of $h[m, n, r]$. We give a proof by induction on $m$. For $m = 0$, the proof goes as follows. By quantifier elimination, any finite set of formulas needed to describe $\varphi$ can be taken to be valued field quantifier free. It follows that

$$(\varphi_{K_1}) = \varphi_{K_2}$$

for $K_1$ and $K_2$ in $\mathcal{C}_{O,N}$ with $k_{K_1} \simeq k_{K_2}$ and $N$ large enough, since two ultraproducts $K = \prod_{i \in I} K_i$ and $K' = \prod_{i \in I'} K_i'$ of fields $K_i$ and $K_i'$ in $\mathcal{C}_O$ with $k_{K_i} \simeq k_{K_i'}$ over a nonprincipal ultrafilter $U$ on a set $I$ are elementary equivalent, as soon as $K$ and $K'$ have characteristic zero.

Now assume $m > 0$. By applying inductively the Cell Decomposition Theorem 2.2.1 we can construct a $\mathcal{L}_O$-definable morphism

$$f : \Lambda \to h[0, n', r']$$

for some $n', r'$, and $\tilde{\varphi} \in \mathcal{C}(h[0, n', r'], \mathcal{L}_O)^e$, such that $\varphi = f^*(\tilde{\varphi})$. Necessarily, $\tilde{\varphi}$ is unique. By the induction hypothesis,

$$\tilde{\varphi}_{K_1} = 0 \text{ if and only if } \tilde{\varphi}_{K_2} = 0$$

for $K_1$ and $K_2$ in $\mathcal{C}_{O,N}$ with $k_{K_1} \simeq k_{K_2}$ and $N$ large enough. Since $\varphi_{K} = f^*_K(\tilde{\varphi}_{K})$ for $K$ in $\mathcal{C}_{O,N}$ when $N$ is large enough, the result follows for general $m$ and for $\varphi$ in $\mathcal{C}(\Lambda, \mathcal{L}_O)^e$.
In general, when $\varphi$ lies in $\mathcal{C}(\Lambda, \mathcal{L}_O)^{\text{exp}}$, we write $\varphi$ as a finite sum of the form

\begin{equation}
\sum_{i=1}^{\ell} E(g_i)e(\xi_i)[X_i \to \Lambda] \varphi_i,
\end{equation}

with $\varphi_i \in \mathcal{C}(\Lambda, \mathcal{L}_O)$. After finitely partitioning $\Lambda$, we may suppose that there is a partition of $\{1, \ldots, \ell\}$ into parts $B_r$ such that

\begin{equation}
\text{ord}(g_i(x_i) - g_j(x_j)) < 0
\end{equation}

for all $i \in B_{r_1}$, all $j \in B_{r_2}$, all $r_1 \neq r_2$, all $\lambda \in \Lambda$ and all $x_i \in X_i, x_j \in X_j$ lying above $\lambda$, and such that

\begin{equation}
\text{ord}(g_i(x_i) - g_j(x_j)) \geq 0
\end{equation}

for all $i, j \in B_r$, all $r$, all $\lambda \in \Lambda$ and all $x_i \in X_i, x_j \in X_j$ lying above $\lambda$.

9.2.2. Claim. — There exists $N > 0$ such that for all $K$ in $\mathcal{C}_{O, N}$ the statement

\begin{equation}
\varphi_{K, \psi_K} = 0 \text{ for every } \psi_K \in \mathcal{D}_K
\end{equation}

is equivalent to

\begin{equation}
\sum_{i \in B_r} (e(\xi_i)[X_i \to \Lambda] \varphi_i)_{K, \psi_K} = 0 \text{ for every } r \text{ and for every } \psi_K \in \mathcal{D}_K.
\end{equation}

Since the left hand side of (9.2.8) is in fact independent of the choice of character $\psi_K$, the proposition directly follows from the claim and the treatment of the case $\varphi$ in $\mathcal{C}(\Lambda, \mathcal{L}_O)^{\text{exp}}$.

Let us now prove the claim. By compactness there exists $N_0$ such that for all $K \in \mathcal{C}_{O, N_0}$ the partition \{\{B_r\}_r satisfies the following property: for every $i \in B_{r_1}$, every $j \in B_{r_2}$, every $r_1 \neq r_2$, every $\lambda \in \Lambda_K$ and every $x_i \in X_{ik}, x_j \in X_{jk}$ lying above $\lambda$

\begin{equation}
\text{ord}(g_{ik}(x_i) - g_{jk}(x_j)) < 0,
\end{equation}

and, for every $i, j \in B_r$, every $r$, every $\lambda \in \Lambda_K$ and every $x_i \in X_{ik}, x_j \in X_{jk}$ lying above $\lambda$,

\begin{equation}
\text{ord}(g_{ik}(x_i) - g_{jk}(x_j)) \geq 0.
\end{equation}

Now the claim follows from Lemma 9.2.3.

9.2.3. Lemma. — Let $K$ be in $\mathcal{C}_O$. Let $c_i$ be in $\mathcal{C}$ and $x_i \in K$ with $\text{ord}(x_i - x_j) < 0$ for $i \neq j, i, j = 1, \ldots, n$. For every $\psi$ in $\mathcal{D}_K$ consider the exponential sum

\[ S_\psi := \sum_{i=1}^{n} c_i \psi(x_i). \]

Suppose that $S_\psi = 0$ for all $\psi$ in $\mathcal{D}_K$. Then $c_i = 0$ for all $i$. 

Thus, the vanishing of $S \otimes A$ with $\zeta$ in one to one correspondence with the set of tuples $(\zeta_{j,i})_j$, via $\psi \mapsto (\psi(y_j))$. Indeed, such characters are determined by their value on $y_1, \ldots, y_r$, hence if we denote by $\zeta_{j,i}$, for $1 \leq i \leq p$, the $p$ distinct complex numbers such that $\zeta_{j,i}^p = \psi_0(py_j)$, they are in one to one correspondence with the set of tuples $(\zeta_{j,i})_j$, via $\psi \mapsto (\psi(y_j))$.

We may rewrite $S_\psi$ as

$$S_\psi = \sum_{a \in \{0, \ldots, p-1\}^r} \prod_{1 \leq j \leq r} \psi(y_j)^{a_j} S_{a,\psi_0}$$

with

$$S_{a,\psi_0} = \sum_{x_i \in B_a} c_i \psi_0(x_i - \sum_{1 \leq j \leq r} a_j y_j).$$

For fixed $j$, the $p \times p$-matrix $A_j := (\zeta_{j,i}^\ell)_{i,\ell}$, $0 \leq \ell \leq p - 1$, is an invertible Vandermonde matrix. It follows that the Kronecker (tensor) product matrix $A_1 \otimes \cdots \otimes A_r$ with coefficients $\prod_{1 \leq j \leq r} \zeta_{j,i}^{\ell_j}$, $0 \leq \ell_j \leq p - 1$, is an invertible $p^r \times p^r$-matrix. Thus, the vanishing of $S_\psi$ for every $\psi$ in $D_K(m)$ implies the vanishing of all the sums $S_{a,\psi_0}$ for every $\psi_0$ in $D_K(m-1)$, and the induction hypothesis allows to conclude.

Now we can prove the following fundamental transfer principle for exponential integrals:

**9.2.4. Theorem** (Transfer principle for exponential integrals)

Let $S \rightarrow \Lambda$ and $S' \rightarrow \Lambda$ be morphisms in $\text{Def}(\mathcal{L}_\mathcal{O})$. Let $\varphi$ be in $\text{IC}(S \rightarrow \Lambda, \mathcal{L}_\mathcal{O})^{\exp}$ and $\varphi'$ in $\text{IC}(S' \rightarrow \Lambda, \mathcal{L}_\mathcal{O})^{\exp}$. Then, there exists an integer $N$ such that for all $K_1, K_2$ in $\mathcal{L}_\mathcal{O}, N$ with $k_{K_1} \simeq k_{K_2}$ the following holds

$$\mu_{K_1}(\varphi_{K_1,\psi_{K_1}}) = \mu_{K_1}(\varphi'_{K_1,\psi_{K_1}}) \text{ for all } \psi_{K_1} \in D_{K_1}$$

if and only if

$$\mu_{K_2}(\varphi_{K_2,\psi_{K_2}}) = \mu_{K_2}(\varphi'_{K_2,\psi_{K_2}}) \text{ for all } \psi_{K_2} \in D_{K_2}.$$
K_1, K_2 in C_{\text{O}, N} with k_{K_1} \simeq k_{K_2} the following holds:
\[ \mu_{\Lambda K_1}(\varphi_{K_1}, \psi_{K_1}) = 0 \text{ for all } \psi_{K_1} \in D_{K_1} \]
if and only if
\[ \mu_{\Lambda K_2}(\varphi_{K_2}, \psi_{K_2}) = 0 \text{ for all } \psi_{K_2} \in D_{K_2}, \]
which follows directly from Theorem 9.1.5 and Proposition 9.2.1.

\textbf{9.2.5. Remark.} — Without exponentials, a form of Theorem 9.2.4 can already be found in [9]. As mentioned in the introduction, it should have a wide range of applications to p-adic representation Theory and the Langlands Program, in particular to various forms of the Fundamental Lemma. Let us note in our approach there is no need any more to make assumptions of local constancy, as was done in [12].

Let us recall that the Fundamental Lemma for unitary groups has been proved by Laumon and Ngô [26] over functions fields and that Waldspurger deduced the case of p-adic fields [31] by representation theoretic techniques. A typical situation when Theorem 9.2.4 can be directly applied is the Jacquet-Ye conjecture [24], a relative version of the Fundamental Lemma involving integrals of additive characters, which has been proved by Ngô [27] over functions fields and by Jacquet [25] in general.

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