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Inter-universal Teichmüller Theory as an Anabelian Gateway to Diophantine Geometry and Analytic Number Theory

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1. Overview via a famous quote of Poincaré

One question that is frequently asked concerning inter-universal Teichmüller theory (IUT) is the following:

> Why/how does IUT allow one to apply **anabelian geometry** to prove **diophantine** results?

In this report, we address this question by giving an *overview of various aspects of IUT*, many of which may be regarded as *striking examples* of the famous quote of *Poincaré* to the effect that

> "**mathematics is the art of giving the same name to different things**"

— which was apparently *originally motivated* by various observations on the part of Poincaré concerning certain remarkable similarities between *transformation group symmetries* of modular functions such as *theta functions*, on the one hand, and *symmetry groups* of the *hyperbolic geometry* of the *upper half-plane*, on the other — all of which are *closely related to IUT* (cf. [EssLgc], §1.5; the discussion surrounding (InfH) in [EssLgc], §3.3; [EssLgc], Example 3.3.2). Here, we note that there are (at least) *three ways* in which this quote of *Poincaré* is related to *IUT*:

(1) the *original motivation* of Poincaré (mentioned above),
(2) the key IUT notions of *coricity/multiradiality* (cf. §2.1, §2.2, §3.2 below), and
(3) *new applications* of the *Galois-orbit version of IUT* (cf. §4 below).

One important theme in this context consists of the observation that one may acquire a rough *survey-level* understanding of IUT using only a knowledge of such elementary topics as

(a) the notions of *rings/fields/groups/monoids* (cf. §2 below; [EssLgc], Example 2.4.8) and
(b) the elementary geometry of the *projective line/Riemann sphere/analytic continuation* (cf. §3 below; [EssLgc], Example 2.4.7).

A more detailed exposition of IUT may be found in the *survey texts* [Alien], [EssLgc], as well as, of course, in the original papers [IUTch], which are exposed in the *videos/slides* available at [ExHr21a, ExHr21b].

2. The N-th power map and Galois groups as abstract groups

Let R be an *integral domain* (such as $\mathbb{Z} \subseteq \mathbb{Q}$) equipped with the action of a *group* G, $(\mathbb{Z} \ni)\ N \geq 2$. For simplicity, we assume that $N = 1 + \cdots + 1 \neq 0 \in R$, and that R has *no nontrivial N-th roots of unity.* Write $R^{\triangleright} \subseteq R$ for the *multiplicative monoid* $R \setminus \{0\}$.

Then let us observe that the *N-th power map* on $R^{\triangleright}$ determines an *isomorphism of multiplicative monoids* equipped with actions by G, i.e.,

$$G \curvearrowright \quad R^{\triangleright} \ \stackrel{\sim}{\rightarrow} \ (R^{\triangleright})^N \ (\subseteq R^{\triangleright}) \ \curvearrowleft \ G,$$

that does *not arise* from a *ring homomorphism*, i.e., is clearly *not compatible* with *addition* (cf. our assumption on N!).

2.1. Distinct ring structures. Next, let ${}^{\dagger}R$, ${}^{\ddagger}R$ be *two distinct copies* of the integral domain R, equipped with respective actions by *two distinct copies* ${}^{\dagger}G$, ${}^{\ddagger}G$ of the group G. We shall use similar notation for objects with labels "†", "‡" to the previously introduced notation. Then one may use the *isomorphism of multiplicative monoids* arising from the *N-th power map* discussed above to *glue* together

$${}^{\dagger}G \ \curvearrowright \ {}^{\dagger}R \supseteq ({}^{\dagger}R^{\triangleright})^N \quad \stackrel{\sim}{\leftarrow} \quad {}^{\ddagger}R^{\triangleright} \subseteq {}^{\ddagger}R \ \curvearrowleft \ {}^{\ddagger}G$$

the *ring* ${}^{\dagger}R$ to the *ring* ${}^{\ddagger}R$ along the *multiplicative monoid* $({}^{\dagger}R^{\triangleright})^N \stackrel{\sim}{\leftarrow} {}^{\ddagger}R^{\triangleright}$.

This gluing is *compatible* with the respective actions of ${}^{\dagger}G$, ${}^{\ddagger}G$ relative to the isomorphism ${}^{\dagger}G \stackrel{\sim}{\rightarrow} {}^{\ddagger}G$ given by forgetting the labels "†", "‡", but, since the N-th power map is **not compatible** with **addition** (!), this isomorphism ${}^{\dagger}G \stackrel{\sim}{\rightarrow} {}^{\ddagger}G$ may be regarded either as an isomorphism of (*"coric"*, i.e., *invariant* with respect to the N-th power map) **abstract groups** (cf. the notion of *"inter-universality"*, as discussed in [EssLgc], §3.2, §3.8) or as an isomorphism of groups equipped with actions on certain *multiplicative monoids*, but **not** as an isomorphism of (**"Galois"** — cf. the *classical inner automorphism indeterminacies* of SGA1) groups equipped with actions on *rings/fields.*

2.2. **The multiradial algorithm.** The problem of *describing (certain portions of the) ring structure* of ${}^{\dagger}R$ in terms of the *ring structure* of ${}^{\ddagger}R$ — in a fashion that is *compatible* with the *gluing* and via a *single* algorithm that may be applied to the *common* (cf. *"logical AND $\wedge$"!*) *glued data* to reconstruct *simultaneously* (certain portions of) the ring structures of *both* ${}^{\dagger}R$ and ${}^{\ddagger}R$, up to suitable relatively mild *indeterminacies* (cf. the theory of *crystals*!) — seems (at first glance/in general) to be *hopelessly intractable*[1] (cf. the case where $R = \mathbb{Z}$)!

This is precisely what is *achieved in IUT* (cf. the quote of *Poincaré*!) by means of the **multiradial algorithm** for the **Θ-pilot** via

- **anabelian geometry** (cf. the *abstract groups* ${}^{\dagger}G$, ${}^{\ddagger}G$!),
- the ***p*-adic/complex logarithm** and **theta functions**, and
- **Kummer theory** (to relate **Frobenius-/étale-like** versions of objects).

Thus, in summary,

> the *multiplicative monoid* and *abstract group* structures (but *not* the ring structures!) are *common* (cf. *"logical AND $\wedge$"!*) to †, ‡.

On the other hand, once one *deletes* the *labels* "†", "‡" to secure a "common R", one obtains a *meaningless* situation, where the common glued data may be related via "†" *OR "$\vee$"* via "‡" to the common R, but *not simultaneously* to both.

When $R = \mathbb{Z}$ (or, more generally, the *ring of integers* "$\mathcal{O}_F$" of a number field F — cf. the multiplicative *norm map* $\mathrm{N}_{F/\mathbb{Q}} : F \to \mathbb{Q}$), one may consider the **"height"** $\log(|x|) \in \mathbb{R}$ for $0 \neq x \in \mathbb{Z}$. Then the *N-th power map* corresponds, after passing to *heights*, to *multiplication by N*; the *multiradial algorithm* corresponds to saying that the height is *unaffected (up to a mild error term!)* by *multiplication by N*, i.e., that the *height is bounded.*

3. Conceptual analogies with the projective line/Riemann sphere

Let k be a *field* (which, in fact, could be taken to be an arbitrary ring), R a *k-algebra.* Denote the *units* of a ring by a superscript "$\times$". Write $\mathbb{A}^1$ for the *affine line* Spec $(k[T])$ over k, $\mathbb{G}_{\mathrm{m}}$ for the open subscheme Spec $(k[T, T^{-1}])$ of $\mathbb{A}^1$ obtained by removing the origin.

Recall that the standard coordinate T on $\mathbb{A}^1$ and $\mathbb{G}_{\mathrm{m}}$ determines

$$\textit{natural bijections } \mathbb{A}^1(R) \xrightarrow{\sim} R,\ \mathbb{G}_{\mathrm{m}}(R) \xrightarrow{\sim} R^{\times}$$

that are compatible with the well-known natural structures on $\mathbb{A}^1$ and $\mathbb{G}_{\mathrm{m}}$, respectively, of *ring scheme/(multiplicative) group scheme* over k.

[1]One well-known example may be seen in the situation where, when $N = p$, one works *modulo p* (cf. the point of view of *indeterminacies*, the analogy with *crystals*!), so that there is a *common ring structure* that is *compatible* with the *p-th power map.*

3.1. **Gluing together distinctly labeled ring schemes.** Next, write ${}^{\dagger}\mathbb{A}^1$, ${}^{\ddagger}\mathbb{A}^1$ for the *k-ring schemes* given by *copies* of $\mathbb{A}^1$ equipped with *labels* "†", "‡". Observe that there exists a *unique isomorphism* of *k-ring schemes* ${}^{\dagger}\mathbb{A}^1 \xrightarrow{\sim} {}^{\ddagger}\mathbb{A}^1$; moreover, there exists a *unique isomorphism* of *k-group schemes* $(-)^{-1} : {}^{\dagger}\mathbb{G}_{\mathrm{m}} \xrightarrow{\sim} {}^{\ddagger}\mathbb{G}_{\mathrm{m}}$ that maps ${}^{\dagger}T \mapsto {}^{\ddagger}T^{-1}$. Note that $(-)^{-1}$ does *not extend* to an isomorphism ${}^{\dagger}\mathbb{A}^1 \xrightarrow{\sim} {}^{\ddagger}\mathbb{A}^1$ and is clearly *not compatible* with the *k-ring scheme structures* of ${}^{\dagger}\mathbb{A}^1$ $(\supseteq {}^{\dagger}\mathbb{G}_{\mathrm{m}})$, ${}^{\ddagger}\mathbb{A}^1$ $(\supseteq {}^{\ddagger}\mathbb{G}_{\mathrm{m}})$.

The *standard construction* of the *projective line* $\mathbb{P}^1$ may be understood as the result of *gluing* ${}^{\dagger}\mathbb{A}^1$ to ${}^{\ddagger}\mathbb{A}^1$ along the isomorphism

$$ {}^{\dagger}\mathbb{A}^1 \supseteq {}^{\dagger}\mathbb{G}_{\mathrm{m}} \xrightarrow{(-)^{-1}} {}^{\ddagger}\mathbb{G}_{\mathrm{m}} \subseteq {}^{\ddagger}\mathbb{A}^1 $$

— i.e., at the level of *R-rational points* ${}^{\dagger}R \supseteq {}^{\dagger}R^{\times} \xrightarrow{(-)^{-1}} {}^{\ddagger}R^{\times} \subseteq {}^{\ddagger}R$ — where ${}^{\Box}R = {}^{\Box}\mathbb{A}^1(R)$, ${}^{\Box}R^{\times} = {}^{\Box}\mathbb{G}_{\mathrm{m}}(R)$, for $\Box \in \{\dagger, \ddagger\}$ (cf. the *gluing* situation discussed in §2, where "$(-)^{-1}$" corresponds to "$(-)^N$"!). In particular, *relative to this gluing*, we observe that there exists a *single rational function* on the copy of "$\mathbb{G}_{\mathrm{m}}$" that appears in the gluing that is *simultaneously* equal to the rational function ${}^{\dagger}T$ on ${}^{\dagger}\mathbb{A}^1$ *AND* [cf. "$\wedge$"!] to the rational function ${}^{\ddagger}T^{-1}$ on ${}^{\ddagger}\mathbb{A}^1$. Thus, in summary,

> the standard construction of $\mathbb{P}^1$ may be regarded as consisting of a *gluing* of two *ring schemes* along an *isomorphism* of *multiplicative group schemes* that is *not compatible* with the *ring scheme* structures on either side of the gluing.

Here, we observe that if, in the gluing under discussion, one *arbitrarily deletes* the *distinct labels* "†", "‡" (e.g., on the grounds that both ring schemes represent "THE" structure sheaf "$\mathcal{O}_X$" of a k-scheme X!), then the resulting *"gluing without labels"* amounts to a gluing of a *single copy* of $\mathbb{A}^1$ to itself that maps the standard coordinate T on $\mathbb{A}^1$ (regarded, say, as a rational function on $\mathbb{A}^1$) to T^{-1}. That is to say, such a *deletion of labels* (even when restricted to the (abstractly isomorphic) multiplicative monoids ${}^{\dagger}T^{\mathbb{Z}}$, ${}^{\ddagger}T^{\mathbb{Z}}$!) immediately results in a *contradiction* (i.e., since $T \neq T^{-1}$!), unless one passes to some sort of *quotient* of $\mathbb{A}^1$, e.g., by introducing some sort of *indeterminacy*, which amounts to the consideration of some sort of *collection of possibilities* [cf. "$\vee$"!].

3.2. **Analogy with the geodesic flow on the Riemann sphere.** When $k = \mathbb{C}$ (i.e., the *complex number field*), one may think of $\mathbb{P}^1$ as the *Riemann sphere* $\mathbb{S}^2$ equipped with the *Fubini-Study metric* and of the gluing under discussion as the gluing, along the *equator* $\mathbb{E}$, of the *northern hemisphere* $\mathbb{H}^+$ to the *southern hemisphere* $\mathbb{H}^-$.

Then the above discussion of standard coordinates "${}^{\dagger}T$", "${}^{\ddagger}T$" translates into the following (at first glance, *self-contradictory*!) phenomenon: an *oriented flow* along the *equator* — which may be thought of physically as a sort of *east-to-west wind current* — appears *simultaneously* to be flowing in the *clockwise* direction, from the point of view of $\mathbb{H}^+ \subseteq \mathbb{S}^2$, *AND* in the *counterclockwise* direction, from the point of view of $\mathbb{H}^- \subseteq \mathbb{S}^2$. Indeed, if one *arbitrarily deletes the labels* "+", "−" and *identifies* $\mathbb{H}^-$ with $\mathbb{H}^+$, then one literally obtains a *contradiction.*

On the other hand, one may relate $\mathbb{H}^-$ to $\mathbb{H}^+$ (*not* by such an arbitrary deletion of labels (!), but rather) by applying the well-known **metric/geodesic geometry/isometric symmetries** of $\mathbb{S}^2$ — i.e., by considering the *geodesic flow* along *great circles/lines of longitude* — to **represent**, up to a *relatively mild distortion*, the entirety of $\mathbb{S}^2$, i.e., including $\mathbb{H}^- \subseteq \mathbb{S}^2$, as a sort of **deformation/displacement** of $\mathbb{H}^+$ (cf. the point of view of *cartography*!).

It is precisely this metric/geodesic/symmetry-based approach that corresponds to the *anabelian geometry*-based *multiradial algorithm for the* Θ*-pilot* in IUT (cf. the analogy discussed in [Alien], §3.1, (iv), (v), as well as in [EssLgc], §3.5, §3.10, between *multiradiality* and *connections/parallel transport/crystals*!).

3.3. **Foundational aspects: universes, diagrams, and data types.** In this context, it is important to remember that, just like SGA, IUT is *formulated entirely in the framework* of **"ZFCG"** (i.e., ZFC, plus Grothendieck's axiom on the existence of universes), especially when considering various *set-theoretic/foundational* aspects of *"gluing"* operations in IUT (cf. [EssLgc], §1.5, §3.8, §3.9, as well as [EssLgc], §3.10, especially the discussion of *"log-shift adjustment"* in (Stp 7)), such as the following:

- gluings are performed at the abstract level of *diagrams* (cf. graphs of groups/anabelioids) and are *not* equipped with any *embedding* into some *familiar ambient space* (like a sphere);
- the *output of reconstruction algorithms* is only well-defined at the level of *objects up to isomorphism* (up to *suitable indeterminacies*), i.e., "types/packages of data" (such as groups, rings, monoids, diagrams, etc.) called *"species"* — one consequence of which is the central importance of *closed loops* in order to obtain *set-theoretic comparisons* that are *not possible at intermediate steps.*

Here, we note the importance of working with

- *"types/packages of data"* (cf., e.g., the *diagrams* referred to above), as opposed to certain particular underlying sets of interest (cf. the classical functoriality of *resolutions* up to *homotopy* in cohomology, as well as of *algebraic closures* of fields up to *conjugacy indeterminacies* — which become unnecessary, e.g., if one considers *norms*), as well as
- the importance of working with **"closed loops"** (cf. *norms* in Galois theory; the classical theory of *analytic continuation/Riemann surfaces* — which is reminiscent of the classical *Riemann-Weierstrass* dispute! (cf. [EssLgc], §1.5); the *geodesic completeness/closed geodesics/isometric symmetries* of the sphere).

4. New enhanced versions of IUT and related work in progress

Recent joint work in progress focuses on the *Section Conjecture ("SC")* in anabelian geometry and allows one (cf. [GSCsp]), using *"resolution of nonsingularities (RNS)"* (cf. [RNSPM]), together with a result of Stoll,

> to reduce the geometricity of an arbitrary Galois section of a hyperbolic curve over a number field to **local geometricity** at each nonarchimedean prime, together with *3 global conditions*, which correspond, respectively, to **3 new enhanced versions of IUT** that are currently under development.

Moreover, this theory of [GSCsp], when combined with other joint work in progress (cf. [AnPf]), has led to substantial progress on the *p-adic SC* that is closely related to the use of *Raynaud-Tamagawa "new-ordinariness"* in the theory of *RNS* (cf. [RNSPM]), and which is noteworthy in that it functions as a sort of *local p-adic analogue of IUT*, via the following analogy: "$\mathrm{Norm}(-) = (-)$" $\longleftrightarrow$ "$N\cdot(-) \approx (-)$" (cf. §2.2).

4.1. **Applications of the Galois-orbit version of IUT.** One such new enhanced version of IUT is the *Galois-orbit version of IUT (GalOrbIUT)*, which implies the following:

- *"intersection-finiteness"*, one of the 3 global conditions mentioned above in the discussion of the *SC*,
- the *nonexistence of Siegel zeroes* of Dirichlet L-functions associated to imaginary quadratic number fields (i.e., by applying the work of Colmez/Granville-Stark/Táfula), and
- a *numerically stronger* version of the *abc/Szpiro* inequalities.

That is to say, we obtain three *a priori different* applications to *anabelian geometry* (the "local-global" SC), *analytic number theory* (nonexistence of Siegel zeroes), and *diophantine geometry* (abc/Szpiro inequalities) — a *striking example* of *Poincaré's quote*, i.e., all three are essentially the **same mathematical phenomenon** of **bounding heights**, i.e., **bounding "local denominators"**.

Indeed, one key aspect of the *local-global SC* application is

> to exhibit IUT as "*anabelian geometry* applied to obtain more *anabelian geometry*"

(hence is less psychologically/intuitively surprising than the other two applications). Other noteworthy aspects include the following:

- it is *technically the most difficult/essential* of the three, i.e., to the extent that the *other two* applications may be thought of, to a substantial extent, as being *"inessential by-products"*;
- it is similar in spirit to the *historical point of view* (cf., e.g., of Grothendieck's famous "letter to Faltings") that suggests (*without any proof!*) that the SC might imply results in diophantine geometry (such as the Mordell Conjecture).

4.2. **Anabelian conceptualization of the abc inequality.** Finally, in this context, it is interesting to recall (cf. [Alien], §3.11, (iii)) that the essential content of *anabelian geometry* may be understood as a sort of **"conceptual translation"** of the *abc inequality*:

> indeed, just as **anabelian geometry** centers around reconstructing *addition* from *multiplication*, the **abc inequality** may be thought of as a bound on the *height (or "additive size")* of a number by the *conductor (or "multiplicative size")* of the number,

i.e., both of these situations exhibit **addition** as being "**dominated** by" **multiplication**. This "conceptual"/"numerical" correspondence is reminiscent of the well-known correspondence between the *conceptual* nature of the *Weil Conjectures* and the corresponding *numerical inequalities* for the number of rational points of a variety over a finite field.

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