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Stable reduction of three point covers

par STEFAN WEWERS

RÉSUMÉ. Cette note est un survol des résultats récents sur la réduction semi-stable des revêtements de la droite projective ramifiés en trois points.

ABSTRACT. This note gives a survey of some recent results on the stable reduction of covers of the projective line branched at three points.

1. Three point covers

1.1. Ramification in the field of moduli.

Let X be a smooth projective curve over \mathbb{C} . A celebrated theorem of Belyi states that X can be defined over a number field K if and only if there exists a rational function f on X with exactly three critical values, see [3], [13]. If such a function f exists, we can normalize it in such a way that the critical values are 0, 1 and ∞ . After this normalization, we may view f as a finite cover $f : X \rightarrow \mathbb{P}^1$ which is étale over $\mathbb{P}^1 - \{0, 1, \infty\}$. We call f a *three point cover*. Another common name for f is *Belyi map*. The *monodromy group* of f is defined as the Galois group of the Galois closure of f .

Let $f : X \rightarrow \mathbb{P}^1$ be a three point cover. By the ‘obvious direction’ of Belyi’s theorem, f can be defined over the field $\bar{\mathbb{Q}}$ of algebraic numbers. Therefore, for every element $\sigma \in \text{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ of the absolute Galois group of \mathbb{Q} we obtain a conjugate three point cover $f^\sigma : X^\sigma \rightarrow \mathbb{P}^1$, which may or may not be isomorphic to f . This yields a continuous action of $\text{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ on the set of isomorphism classes of three point covers. Hence we can associate to f the number field K such that $\text{Gal}(\bar{\mathbb{Q}}/K)$ is precisely the stabilizer of the isomorphism class of f . The field K is called the *field of moduli* of f . Under certain extra assumptions on f , the field K is the smallest field of definition of the cover f , see [6]

Three point covers are determined, up to isomorphism, by finite, purely combinatorial data – e.g. by a *dessin d’enfants* [21]. It is an interesting problem to describe the field of moduli of a three point cover in terms of these data. There are only few results of a general nature on this problem. The aim of this note is to explain certain results leading to the following theorem, proved in [26].

Theorem 1.1. *Let $f : X \rightarrow \mathbb{P}^1$ be a three point cover, with field of moduli K and monodromy group G . Let p be a prime number such that p^2 does not divide the order of G . Then p is at most tamely ramified in the extension K/\mathbb{Q} .*

If the prime p does not divide the order of G then p is even unramified in the extension K/\mathbb{Q} , by a well known theorem of Beckmann [2]. Both Beckmann's result and Theorem 1.1 rely on an analysis of the reduction of f at the prime ideals \mathfrak{p} of K dividing p . The results leading to Theorem 1.1 were mainly inspired by Raynaud's paper [20].

1.2. Good reduction.

To warm up, let us explain the result of Beckmann mentioned above. Fix a prime number p and let K_0 denote the completion of the maximal unramified extension of \mathbb{Q}_p . From now on, the letter K will always denote a finite extension of K_0 . Note that K is complete with respect to a discrete valuation v , with residue field $k = \overline{\mathbb{F}}_p$. We write R (resp. R_0) for the ring of integers of K (resp. of K_0).

Let $f : X \rightarrow Y := \mathbb{P}_K^1$ be a three point cover, defined over a finite extension K/K_0 . Let $\mathcal{Y} := \mathbb{P}_R^1$ denote the standard (smooth) model of Y over R . We say that f has *good reduction* if f extends to a finite tame cover $f_R : \mathcal{X} \rightarrow \mathcal{Y}$, ramified only along the sections $0, 1, \infty$. The map f_R is then called a *good model* for f . Such a good model is unique; moreover, \mathcal{X} is automatically a smooth model of X . In particular, if the cover f has good reduction, then the curve X has good reduction, too. (The converse of this conclusion does not hold.)

The following theorem is a consequence of the theory of the tame fundamental group [10].

Theorem 1.2. *Let $f : X \rightarrow Y = \mathbb{P}_K^1$ be a three point cover over K , with monodromy group G .*

- (1) *If the order of G is prime to p , then f has good reduction.*
- (2) *If f has good reduction, then f has a unique model $f_{K_0} : X_{K_0} \rightarrow \mathbb{P}_{K_0}^1$ over K_0 with good reduction.*

Proof. We only give a sketch of the argument. For more details, see e.g. [17] or [24]. Suppose that f has good reduction, with good model $f_R : \mathcal{X} \rightarrow \mathcal{Y}$. Let $\bar{f} : \bar{X} \rightarrow \bar{Y} = \mathbb{P}_k^1$ denote the special fiber of f_R . By definition, the map \bar{f} is a finite and tame cover of smooth curves over k , ramified at most at $0, 1, \infty$. In other words, \bar{f} is a three point cover in characteristic p .

By a fundamental result of Grothendieck [10], there exists a tame cover $g : \mathcal{X}_0 \rightarrow \mathcal{Y}_0 := \mathbb{P}_{R_0}^1$, ramified at most along $0, 1, \infty$, which lifts \bar{f} . We call g a *lift* of \bar{f} over R_0 . Such a lift is uniquely determined by the choice of the

base curve \mathcal{Y}_0 (which lifts \bar{Y}) and the ramification locus $D := \{0, 1, \infty\} \subset \mathcal{Y}_0$ (which lifts the ramification locus of \bar{f}).

By construction, both $g \otimes_{R_0} R$ and f_R are lifts of \bar{f} over R , with the same base curve \mathcal{Y} and the same ramification locus D . Therefore, by uniqueness, f_R is isomorphic to $g \otimes_{R_0} R$. In particular, the generic fiber of g is a model of f over K_0 with good reduction. This proves (ii).

To prove (i), we may replace the field K by any finite extension. Indeed, if we can show that f has good reduction after an extension of K , then (ii) shows that f is defined and has good reduction already over K_0 .

The cover f gives rise to a finite extension of function fields $K(X)/K(Y)$. We may identify $K(Y)$ with the rational function field $K(t)$, where t is the standard parameter on \mathbb{P}^1 . Let v_0 denote the Gauss valuation on $K(Y) = K(t)$ with respect to t . Let L be the Galois closure of $K(X)/K(Y)$. After replacing K by a finite extension, we can assume that K is algebraically closed in L . Then the Galois group of $L/K(Y)$ can be identified with the monodromy group G of the cover f .

Now suppose that the order of G is prime to p . Then a simple application of Abhyankar’s Lemma shows that, after a further extension of K , the Gauss valuation v_0 is unramified in the extension $L/K(Y)$, and hence in the extension $K(X)/K(Y)$.

Let \mathcal{X} denote the normalization of $\mathcal{Y} := \mathbb{P}_R^1$ inside the function field of X . By definition, the natural map $f_R : \mathcal{X} \rightarrow \mathcal{Y}$ is a finite map which extends $f : X \rightarrow Y$. Moreover, f_R is unramified along the special fiber $\bar{Y} = \mathbb{P}_k^1$, seen as a divisor on \mathcal{Y} . Using the Purity Theorem of Zariski–Nagata, it is now easy to show that f_R is a tame cover, ramified only along the divisor $D = \{0, 1, \infty\} \subset \mathcal{Y}$. In other words, f_R is a good model for f . This proves (i) and concludes the proof of Theorem 1.2. \square

Corollary 1.3 (Beckmann). *Let $f : X \rightarrow \mathbb{P}^1$ be a three point cover (defined over $\bar{\mathbb{Q}}$) with field of moduli K . Let p be a prime number which does not divide the order of the monodromy group of f . Then p is unramified in the extension K/\mathbb{Q} .*

Proof. Let \mathfrak{p} be a place of $\bar{\mathbb{Q}}$ whose residue characteristic is prime to the order of the monodromy group of f . Let $\sigma \in \text{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ be an element of the inertia group of \mathfrak{p} . We claim that $f^\sigma \cong f$. Clearly, this claim implies the corollary.

To prove the claim, let K_0 be the completion of the maximal unramified extension of \mathbb{Q}_p , and let \bar{K}_0 denote an algebraic closure of K_0 . The place \mathfrak{p} gives rise to an embedding $\bar{\mathbb{Q}} \hookrightarrow \bar{K}_0$. Moreover, there exists a (unique) element $\tau \in \text{Gal}(\bar{K}_0/K_0)$ with $\tau|_{\bar{\mathbb{Q}}} = \sigma$. By Theorem 1.2, the three point cover $f_{\bar{K}_0} := f \otimes \bar{K}_0$ can be defined over K_0 . Hence we have $f_{\bar{K}_0}^\tau \cong f_{\bar{K}_0}$, which implies $f^\sigma \cong f$. This proves the claim and the corollary. \square

The basic strategy to prove Theorem 1.1 is quite similar to the proof of Corollary 1.3. One first studies the reduction of the cover f at a prime ideal \mathfrak{p} , and then one uses a lifting result. The main difficulty is that, if p divides the order of G , the cover f will in general not have good reduction at p . So both for the reduction and the lifting step, one can not use the standard results of Grothendieck. In the following two sections we explain two results (Theorem 2.4 and Theorem 3.1) which replace Part (i) and (ii) of Theorem 1.2 in the case where p exactly divides the order of G .

2. Stable reduction

2.1. The semistable reduction theorem.

Let K be a field equipped with a discrete valuation v . We denote by R the valuation ring of v and by k its residue class field. Let X be a smooth projective curve over K . We assume that X is geometrically irreducible. By a *model* of X over R we mean a flat proper R -scheme \mathcal{X} such that $\mathcal{X} \otimes_R K = X$. For instance, if we fix a projective embedding $X \hookrightarrow \mathbb{P}_K^n$, then the Zariski closure of X inside \mathbb{P}_R^n is a model of X over R . One can show that, conversely, every model of X arises in this way (for some projective embedding of X).

We say that X has *good reduction* if there exists a model \mathcal{X} such that the special fiber $\bar{X} := \mathcal{X} \otimes_R k$ is a smooth curve over k . In this case, \mathcal{X} is called a *good model* of X . If the genus of X is > 0 , then there exists at most one good model, up to isomorphism.

In general, X may not have good reduction. A very basic and important problem in arithmetic geometry is to find models of X which are still reasonably nice to work with. For many questions, the *regular models* are a good choice. However, for the questions we are concerned with in this article (and for many other questions too), regular models are not the right choice.

Definition 2.1. A model \mathcal{X} of X over R is called *semistable*, if the special fiber \bar{X} is a reduced curve with at worst ordinary quadratic singularities. We say that X has *semistable reduction* if there exists a semistable model over R .

Semistable models are never unique. Indeed, blowing up \mathcal{X} in any smooth point of the special fiber will produce another semistable model dominating \mathcal{X} . However, if X has semistable reduction and the genus of X is ≥ 2 , then there exists a semistable model \mathcal{X} which is minimal (with respect to domination). It is called the *stable model*, see [7].

The following theorem is a cornerstone of modern arithmetic geometry.

Theorem 2.2 (Semistable Reduction). *Let X be a smooth projective curve over K . Then there exists a finite extension K'/K such that the curve $X' := X \otimes_K K'$ has semistable reduction.*

In full generality, this theorem was first proved by Deligne and Mumford [7]. For an overview, see e.g. [1]. We would like to stress that Theorem 2.2 is a mere existence result. Even for curves X given by very simple equations, it can be extremely difficult to determine a finite extension K'/K over which X has semistable reduction. The difficulty comes from the fact that one may be forced to take an extension K'/K which is wildly ramified. (Indeed, if the residue class field k has characteristic 0, and hence K'/K can only be tamely ramified, the proof of Theorem 2.2 is relatively easy.) Recent work of Lehr and Matignon [14] treats the case of p -cyclic covers of the projective line, i.e. curves X which are birationally given by an equation of the form $y^p = f(x)$, with $f(x) \in K[x]$.

2.2. The stable model of a Galois cover.

Let K_0 be as in §1.2, and let $f : X \rightarrow \mathbb{P}_K^1$ be a three point cover, defined over a finite extension K/K_0 . If p divides the order of the monodromy group, then f may have bad reduction and it may not be possible to define f over K_0 . For the purpose of studying this situation, it is no restriction to make the following additional assumptions.

- The cover $f : X \rightarrow \mathbb{P}_K^1$ is Galois, with Galois group G (replace f by its Galois closure).
- The curve X has semistable reduction (replace K by a finite extension).

Note that passing to the Galois closure may already force us to replace K by a finite extension. But this is ok if we only want to bound K from above, e.g. to show that we may take K/K_0 to be tamely ramified. For the second point, we have used Theorem 2.2. For simplicity, we shall also assume that the genus of X is ≥ 2 . (Three point Galois covers of genus ≤ 1 can be classified and treated separately.)

Let \mathcal{X} denote the stable model of X , i.e. the minimal semistable model of X over the ring of integers of K , see [7]. By uniqueness of the stable model, the action of G on X extends to \mathcal{X} . Let $\mathcal{Y} := \mathcal{X}/G$ be the quotient scheme. It is shown in [18], Appendice, that \mathcal{Y} is again a semistable curve over R .

Definition 2.3. The morphism $f^{\text{st}} : \mathcal{X} \rightarrow \mathcal{Y}$ is called the *stable model* of f . Its special fiber $\bar{f} : \bar{X} \rightarrow \bar{Y}$ is called the *stable reduction* of f .

If \bar{f} is a separable and tamely ramified map between smooth curves, then f has good reduction, in the sense of §1.2. Otherwise, we say that f has bad reduction.

Initiated by a series of papers by Raynaud [18], [19], [20], several authors have studied the stable reduction of covers of curves (the case of three point covers is just a special case). For an overview of their results and a more extensive list of references, see [15]. In this note, we shall focus on the results of [26], and on results which inspired this work (mainly [20], [11], [25]).

2.3. Bad reduction.

Let $\bar{f} : \bar{X} \rightarrow \bar{Y}$ be the stable reduction of a three point cover $f : X \rightarrow \mathbb{P}_K^1$. We suppose that f has bad reduction. Let (\bar{Y}_i) be the list of all irreducible components of the curve \bar{Y} . Since the generic fiber of \mathcal{Y} is just the projective line, the components \bar{Y}_i are all smooth curves of genus 0. Moreover, the graph of components of \bar{Y} (whose vertices are the components \bar{Y}_i and whose edges are the singular points) is a tree. For each index i , we fix an irreducible component \bar{X}_i of \bar{X} such that $\bar{f}(\bar{X}_i) = \bar{Y}_i$. Let $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ denote the restriction of \bar{f} to \bar{X}_i . Let $G_i \subset G$ denote the stabilizer of the component \bar{X}_i .

The component \bar{Y}_i corresponds to a discrete valuation v_i of the function field $K(Y)$ of $Y = \mathbb{P}_K^1$ whose residue field is the function field of \bar{Y}_i . The choice of \bar{X}_i corresponds to the choice of a valuation w_i of the function field $K(X)$ of X extending v_i , and the map \bar{f}_i corresponds to the residue field extension of $w_i|v_i$. The group G_i is simply the decomposition group of w_i in the Galois extension $K(X)/K(Y)$. Let $I_i \triangleleft G_i$ denote the corresponding inertia group.

By definition of the semistable model, the curve \bar{X} is reduced. It follows that the ramification index $e(w_i|v_i)$ of the extension of valuations is equal to one. This does not mean that the extension in question is unramified at the valuation w_i : the residue field of w_i is a function field in one variable over k and hence not perfect. However, it follows that the inertia group I_i is a p -group whose order is equal to the degree of inseparability of the extension of residue fields.

We say that \bar{Y}_i is a *good component* if the map \bar{f}_i is separable. By what we have said above, this holds if and only if $I_i = 1$, i.e. the valuation v_i is unramified in the extension $K(X)/K(Y)$. If this is the case, then $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ is a Galois cover with Galois group G_i .

If \bar{f}_i is not separable we say that \bar{Y}_i is a *bad component*. The map \bar{f}_i factors as the composition of a purely inseparable map $\bar{X}_i \rightarrow \bar{Z}_i$ of degree $|I_i|$ and a Galois cover $\bar{Z}_i \rightarrow \bar{Y}_i$ with Galois group G_i/I_i . By assumption, there exists at least one bad component.

Note that $K(Y) = K(t)$, where t is the standard parameter on \mathbb{P}^1 . To simplify the exposition, we shall make the following additional assumption: there is a (necessarily unique) component \bar{Y}_0 of \bar{Y} which corresponds to the Gauss valuation on $K(t)$ with respect to the parameter t . This component

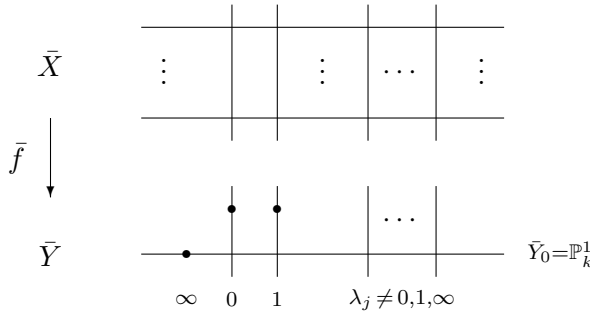


FIGURE 1. The stable reduction of a three point cover

is called the *original component*. It is canonically isomorphic to \mathbb{P}_k^1 . (It may be that there is no component of \bar{Y} corresponding to the Gauss valuation. This happens if and only if the cover f has bad reduction but the curve X has good reduction. In [26], Definition 2.1, this is called the *exceptional case*.) Let $\bar{Y}_1, \dots, \bar{Y}_r$ be the components of \bar{Y} different from \bar{Y}_0 .

The following theorem is the first main result of [26].

Theorem 2.4. *Suppose that p strictly divides the order of G and that f has bad reduction. Then the following holds (compare with Figure 1).*

- (1) *The original component \bar{Y}_0 is the only bad component. Every good component \bar{Y}_i intersects \bar{Y}_0 in a unique point $\lambda_i \in \bar{Y}_0$.*
- (2) *The inertia group I_0 corresponding to the bad component \bar{Y}_0 is cyclic of order p . The subcover $\bar{Z}_0 \rightarrow \bar{Y}_0$ of \bar{f}_0 (which is Galois with group G_0/I_0), is ramified at most in the points λ_i (where \bar{Y}_0 intersects a good component).*
- (3) *For $i = 1, \dots, r$, the Galois cover $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ is wildly ramified at the point λ_i and tamely ramified above $\bar{Y}_i - \{\lambda_i\}$. If $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ is ramified at a point $\neq \lambda_i$, then this point is the specialization of one of the three branch points $0, 1, \infty$ of the cover $f : X \rightarrow \mathbb{P}_K^1$.*

Part (ii) and (iii) of this theorem follow from part (i), by the results of [20]. In fact, this implication is not restricted to three point covers but holds for much more general covers $f : X \rightarrow Y$. On the other hand, the truth of part (i) depends in an essential way on the assumption that f is a three point cover.

Under the additional assumption that all the ramification indices of f are prime to p , Theorem 2.4 follows already from the results of [25], via Raynaud’s construction of the *auxiliary cover* (see the introduction of [25]).

Here is a brief outline of the proof of Theorem 2.4. First, certain general results on the stable reduction of Galois covers, proved in [20], already

impose severe restrictions on the map \bar{f} . For instance, it is shown that the good components are precisely the *tails* of \bar{Y} (i.e. the leaves of the tree of components of \bar{Y}). Also, the Galois covers $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ (if \bar{Y}_i is good) and $\bar{Z}_i \rightarrow \bar{Y}_i$ (if \bar{Y}_i is bad) are ramified at most at the points which are either singular points of the curve \bar{Y} or specialization of a branch point of f .

In the next step one defines, for each bad component \bar{Y}_i , a certain differential form ω_i on the Galois cover $\bar{Z}_i \rightarrow \bar{Y}_i$. This differential form satisfies some very special conditions, relative to the map $\bar{f} : \bar{Y} \rightarrow \bar{X}$ and the action of G on \bar{Y} . For instance, ω_i is either logarithmic (i.e. of the form du/u) or exact (i.e. of the form du). Furthermore, ω_i is an eigenvector under the action of the Galois group G_i/I_i of the cover $\bar{Z}_i \rightarrow \bar{Y}_i$, and its zeros and poles are related to and determined by the ramification of the map $\bar{f} : \bar{Y} \rightarrow \bar{X}$. These properties follow from the work of Henrio [11]. Let us say for short that ω_i is *compatible* with \bar{f} . Intuitively, ω_i encodes infinitesimal information about the action of the inertia group I_i on the stable model \mathcal{X} , in a neighborhood of the component \bar{X}_i . Within the proof of Theorem 2.4, the important point is that the existence of the compatible differentials ω_i imposes further restrictions on the map $\bar{f} : \bar{X} \rightarrow \bar{Y}$. In fact, these restrictions are strong enough to prove part (i) of Theorem 2.4. For details, see [26], §2.1.

2.4. Special deformation data.

By Theorem 2.4 (i), the original component $\bar{Y}_0 = \mathbb{P}_k^1$ is the only bad component for the stable reduction of the three point cover f . The proof of Theorem 2.4 shows that there exists a differential form ω_0 on the Galois cover $\bar{Z}_0 \rightarrow \bar{Y}_0$ which is compatible with \bar{f} , in the sense explained above. It is worthwhile to write down explicitly what ‘compatibility’ implies for the differential ω_0 .

To simplify the exposition, we assume that the ramification indices of f are all divisible by p . If this is the case, then the branch points $0, 1$ and ∞ specialize to the original component \bar{Y}_0 . Since we identify \bar{Y}_0 with \mathbb{P}_k^1 , this means that the points $\lambda_1, \dots, \lambda_r$ where \bar{Y}_0 intersects the good components $\bar{Y}_1, \dots, \bar{Y}_r$ are distinct from $0, 1, \infty$. By Theorem 2.4 (iii), the Galois covers $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ are then étale over $\bar{Y}_i - \{\lambda_i\}$.

Let t denote the rational function on the original component \bar{Y}_0 which identifies it with \mathbb{P}_k^1 . Compatibility of ω_0 with \bar{f} implies that

$$(1) \quad \omega_0 = c \cdot \frac{z dt}{t(t-1)},$$

where $c \in k^\times$ is a constant and z is a rational function on \bar{Z}_0 for which an equation of the form

$$(2) \quad z^{p-1} = \prod_i (t - \lambda_i)^{a_j}$$

holds. Here the a_i are integers $1 < a_i < p$ such that $\sum_i a_i = p - 1$. These integers are determined by the (wild) ramification of the Galois covers $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ at λ_i .

Compatibility of ω_0 with \bar{f} also implies that ω_0 is logarithmic, i.e. is of the form du/u , for some rational function u on \bar{Z}_0 . Equivalently, ω_0 is invariant under the Cartier operator. The latter condition gives a finite list of equations satisfied by the t -coordinates of the points λ_i (depending on the numbers a_i). One can show that these equations have only a finite number of solutions (λ_i), see [23], Theorem 5.14. In other words, the existence of the differential form ω_0 determines the position of the points λ_i , up to a finite number of possibilities.

The pair (\bar{Z}_0, ω_0) is called a *special deformation datum*. Given a special deformation datum (\bar{Z}_0, ω_0) , the branch points λ_i of the cover $\bar{Z}_0 \rightarrow \bar{Y}_0$ are called the *supersingular points*. A justification for this name, in form of a well known example, will be given in §4. By the result mentioned in the preceding paragraph, a special deformation datum is *rigid*, i.e. is an object with 0-dimensional moduli. This is no surprise, as special deformation data arise from three point covers, which are rigid objects themselves. We point this out, because this sort of rigidity is the (somewhat hidden) principle underlying all results discussed in this note which are particular for three point covers. In the following section, we will interpret the existence of (\bar{Z}_0, ω_0) as a liftability condition for the map $\bar{f} : \bar{X} \rightarrow \bar{Y}$.

3. Lifting

3.1. Special G -maps.

The stable reduction of a three point Galois cover $f : X \rightarrow \mathbb{P}_K^1$ is, by definition, a finite map $\bar{f} : \bar{X} \rightarrow \bar{Y}$ between semistable curves over the residue field k , together with an embedding $G \hookrightarrow \text{Aut}(\bar{X}/\bar{Y})$. In the case of bad reduction, the curves \bar{Y} and \bar{X} are singular, and the map \bar{f} is inseparable over some of the components of \bar{Y} . This suggests the following question. Given a map $\bar{f} : \bar{X} \rightarrow \bar{Y}$ of the sort we have just described, together with an embedding $G \hookrightarrow \text{Aut}(\bar{X}/\bar{Y})$, does it occur as the stable reduction of a three point Galois cover $f : X \rightarrow \mathbb{P}_K^1$, for some finite extension K/K_0 ? If this is the case, then we say that $f : X \rightarrow \mathbb{P}_K^1$ is a *lift* of $\bar{f} : \bar{X} \rightarrow \bar{Y}$.

Theorem 2.4 and its proof give a list of necessary conditions on \bar{f} for the existence of a lift (at least under the extra condition that p strictly divides the order of G). These conditions lead naturally to the notion of a *special G -map*. See [26], §2.2 for a precise definition. To give the general idea, it suffices to say that a special G -map is a finite map $\bar{f} : \bar{X} \rightarrow \bar{Y}$ between semistable curves, together with an embedding $G \hookrightarrow \text{Aut}(\bar{X}/\bar{Y})$, which admits a compatible special deformation datum (\bar{Z}_0, ω_0) . One can

show that special G -maps are rigid in the sense we used at the end of §2.4. Moreover, one has the following lifting result, proved in [26], §4.

Theorem 3.1. *Let $\bar{f} : \bar{X} \rightarrow \bar{Y}$ be a special G -map over k . Then the following holds.*

- (1) *There exists a three point cover $f : X \rightarrow \mathbb{P}^1$ lifting \bar{f} .*
- (2) *Every lift f of \bar{f} can be defined over a finite extension K/K_0 which is at most tamely ramified.*

The corresponding result proved in [26], §4, is somewhat stronger. It determines the set of isomorphism classes of all lifts of \bar{f} , together with the action of $\text{Gal}(\bar{K}_0/K_0)$, in terms of certain invariants of \bar{f} (these invariants are essentially the numbers a_i appearing in (2)). This more precise result gives an upper bound for the degree of the minimal extension K/K_0 over which every lift of \bar{f} can be defined.

Theorem 1.1 follows easily from Theorem 2.4 and Theorem 3.1 (in a way similar to how Beckmann's Theorem follows from Grothendieck's theory of tame covers, see the proof of Corollary 1.3).

Part (i) of Theorem 3.1, i.e. the mere existence of a lift, follows already from the results of [25]. Part (ii) is more difficult. The technical heart of the proof is a study of the deformation theory of a certain curve with an action of a finite group scheme, which is associated to a special deformation datum. A detailed exposition of this deformation theory can be found in [23]. An overview of the proof of Theorem 3.1 will be given in §3.4 below.

3.2. The supersingular disks.

Let $f : Y \rightarrow \mathbb{P}_K^1$ be a three point cover, defined over a finite extension K/K_0 , with bad reduction. Let $\bar{f} : \bar{X} \rightarrow \bar{Y}$ be the stable reduction of f . We assume that the conclusion of Theorem 2.4 holds (it holds, for instance, if $p^2 \nmid |G|$). Let Y^{an} denote the rigid analytic K -space associated to $Y = \mathbb{P}_K^1$. The R -model \mathcal{Y} of Y yields a specialization map $\text{sp}_{\mathcal{Y}} : Y^{\text{an}} \rightarrow \bar{Y}$. For $i = 1, \dots, r$, the good component \bar{Y}_i gives rise to a rigid analytic subset

$$D_i := \text{sp}_{\mathcal{Y}}^{-1}(\bar{Y}_i - \{\lambda_i\}) \subset Y^{\text{an}}.$$

As a rigid K -space, D_i is a closed unit disk, i.e. is isomorphic to the affinoid $\text{Spm } K\{\{T\}\}$. See e.g. [12].

An important step in the proof of Part (ii) of Theorem 3.1 is to show that the disks D_i depend only on the reduction \bar{f} , but not on the lift f of \bar{f} . For simplicity, we shall again assume that all the ramification indices of the three point cover $f : X \rightarrow \mathbb{P}_K^1$ are divisible by p , see §2.4. Then the special deformation datum (\bar{Z}_0, ω_0) associated to the reduction $\bar{f} : \bar{X} \rightarrow \bar{Y}$ is essentially determined by points $\lambda_1, \dots, \lambda_r \in \mathbb{P}_k^1 - \{0, 1, \infty\}$ and integers a_1, \dots, a_r with $1 < a_i < p$ and $\sum_i a_i = p - 1$. We consider λ_i as an element

of $k - \{0, 1\}$ and let $\tilde{\lambda}_i \in R_0$ be a lift of λ_i . By definition, the closed disk D_i is contained in the open unit disk

$$D'_i := \{t \in R \mid |t - \tilde{\lambda}_i|_K < 1\} \subset Y^{\text{an}}.$$

With this notation, we have the following result, see [26], Proposition 4.3 and the remark following the proof of Theorem 3.8.

Proposition 3.2. *We have*

$$D_i = \{t \in D'_i \mid |t - \tilde{\lambda}_i|_K \leq |p|_K^{\frac{p}{p-1+a_i}}\}.$$

In particular, the disks D_i depend only on the special deformation datum (\bar{Z}_0, ω_0) .

We call the open disks D'_i the *supersingular disks* associated to the special deformation datum (\bar{Z}_0, ω_0) . This is in correspondence with naming the points $\lambda_i \in \bar{Y}_0$ the supersingular points, see §2.4. The closed subdisk $D_i \subset D'_i$ is called the *too supersingular disk*, a term which is also borrowed from the theory of moduli of elliptic curves, see §4.

3.3. The auxiliary cover.

We continue with the notation and assumptions of the preceding subsection. Recall that we have chosen in §2.3 a component $\bar{X}_i \subset \bar{X}$ above the component $\bar{Y}_i \subset \bar{Y}$. The stabilizer of \bar{X}_i is the subgroup $G_i \subset G$ and the inertia subgroup of \bar{X}_i is a normal subgroup $I_i \triangleleft G_i$. By the conclusion of Theorem 2.4, we have $|I_0| = p$ and $|I_i| = 1$ for $i = 1, \dots, r$. Let $\bar{X}^{\text{hor}} \subset \bar{X}$ denote the union of all *horizontal* components, i.e. those components of \bar{X} which are mapped onto the original component \bar{Y}_0 . Then we have

$$f^{-1}(D_i) = \text{Ind}_{G_i}^G(E_i), \quad \text{with } E_i = \text{sp}_{\mathcal{X}}^{-1}(\bar{X}_i - \bar{X}^{\text{hor}}) \subset X^{\text{an}}.$$

The map $E_i \rightarrow D_i$ is a finite étale Galois cover between smooth affinoid K -spaces whose reduction is equal to the restriction of the étale Galois cover $\bar{f}_i^{-1}(\bar{Y}_i - \{\lambda_i\}) \rightarrow \bar{Y}_i - \{\lambda_i\}$. This determines $E_i \rightarrow D_i$ uniquely, up to isomorphism, because lifting of étale morphisms is unique.

Let $U_0 := Y^{\text{an}} - (\cup_i D_i)$ denote the complement of the disks D_i . Then we have

$$f^{-1}(U_0) = \text{Ind}_{G_0}^G(V_0), \quad \text{with } V_0 := \text{sp}_{\mathcal{X}}^{-1}(\bar{X}^{\text{hor}}) \subset X^{\text{an}}.$$

The map $V_0 \rightarrow U_0$ is a finite Galois cover between smooth (non quasi-compact) rigid K -spaces, étale outside the subset $\{0, 1, \infty\} \subset U_0$. It can be shown that there exists a G_0 -Galois cover $f^{\text{aux}} : X^{\text{aux}} \rightarrow Y = \mathbb{P}_K^1$ such that $V_0 = (f^{\text{aux}})^{-1}(U_0)$. Such a cover f^{aux} is ramified at $0, 1, \infty$ and, for each $i = 1, \dots, r$, at one point $y_i \in D'_i$. Moreover, the cover f^{aux} is uniquely determined by the choice of the points y_i . It is called the *auxiliary cover* associated to f and the points (y_i) , see [20], [25] and [26], §4.1.3. Let ∂D_i

denote the boundary of the disk D_i . By construction of f^{aux} , there exists a G -equivariant isomorphism

$$(3) \quad \varphi_i : \text{Ind}_{G_i}^G (E_i \times_{D_i} \partial D_i) \cong \text{Ind}_{G_0}^G (f^{\text{aux}})^{-1}(\partial D_i),$$

compatible with the natural map to ∂D_i .

3.4. The proof of Theorem 3.1.

We will now give a brief outline of the proof of Theorem 3.1. Suppose that $\bar{f} : \bar{X} \rightarrow \bar{Y}$ is a special G -map. We want to construct all three point covers $f : X \rightarrow Y = \mathbb{P}_K^1$ lifting \bar{f} . For the moment, we let K be any sufficiently large finite extension of K_0 . At the end of our argument, we will reason that it suffices to take for K a certain tame extension of K_0 , which is explicitly determined by \bar{f} .

We divide the proof into three steps. The first step consists in constructing a Galois cover $f^{\text{aux}} : X^{\text{aux}} \rightarrow Y$ which can play the role of the auxiliary cover associated to any lift f of \bar{f} . In fact, one shows that all good candidates f^{aux} live in a continuous family which depends only on the special deformation datum (\bar{Z}_0, ω_0) associated to \bar{f} . The individual members of this family depend on the choice of the extra branch points $y_i \in D'_i$ (with D'_i as above). See [25], §3.2, and [26], §3.

Let $D_i \subset D'_i$ be the closed disk defined in Proposition 3.2 (the numbers a_i used in the definition of D_i are determined by the special deformation datum (\bar{Z}_0, ω_0)). Let $E_i \rightarrow D_i$ be the étale G_i -Galois cover lifting $\bar{f}_i^{-1}(\bar{Y}_i - \{\lambda_i\}) \rightarrow \bar{Y}_i - \{\lambda_i\}$. For any choice of points $y_i \in D'_i$, we obtain a cover $f^{\text{aux}} : X^{\text{aux}} \rightarrow Y$, which is a candidate for the auxiliary cover. In this situation, a tuple (φ_i) of isomorphisms as in (3) is called a *patching datum*.

The second step of the proof consists in showing that there exists a patching datum (φ_i) if and only if the points y_i lie in the smaller disk D_i . The sufficiency of the condition $y_i \in D_i$ can be shown using the same arguments as in [25], §3.4. The necessity of this condition – which is equivalent to Proposition 3.2 above – lies somewhat deeper. See [26], §3, in particular Theorem 3.8. In this step one uses the deformation theory developed in [23].

The third and final step uses rigid (or formal) patching. For any choice of $y_i \in D_i$, let $f^{\text{aux}} : X^{\text{aux}} \rightarrow Y = \mathbb{P}_K^1$ be the associated auxiliary cover, and set $V_0 := (f^{\text{aux}})^{-1}(U_0)$. By the second step, we have a patching datum (φ_i) . The proof of the claim in step two shows moreover that the cover $V_0 \rightarrow U_0$ depends only on the special deformation datum, but not on the choice of $y_i \in D_i$. Using rigid patching, one easily constructs a G -Galois cover $f : X \rightarrow Y$ such that $f^{-1}(D_i) = \text{Ind}_{G_i}^G(E_i)$, $f^{-1}(U_0) = \text{Ind}_{G_0}^G(V_0)$ and such that the patching datum (φ_i) is induced by the identity on X . Essentially by construction, f is a three point cover lifting the special G -map \bar{f} . This proves Part (i) of Theorem 3.1.

It is not hard to see that all lifts of \bar{f} arise in the way we have just described. More precisely, the set of isomorphism classes of lifts of f is in bijection with the set of patching data. Therefore, to finish the proof of Theorem 3.1 it suffices to show that the above construction works over a tame extension K/K_0 . Actually, the construction of the covers $E_i \rightarrow D_i$ and of the auxiliary cover $f^{\text{aux}} : X^{\text{aux}} \rightarrow Y$ can be done over K_0 (set $y_i := \tilde{\lambda}_i$). A direct analysis shows that patching data (φ_i) exist if one takes for K the (unique) tame extension of degree $(p-1) \cdot \text{lcm}_i(p-1+a_i)$. This concludes the proof of Theorem 3.1.

4. Modular curves

4.1. Modular curves as three point covers.

Let \mathbb{H} denote the upper half plane and \mathbb{H}^* the union of \mathbb{H} with the set $\mathbb{P}^1(\mathbb{Q})$. The group $\text{SL}_2(\mathbb{Z})$ acts on \mathbb{H} and \mathbb{H}^* in a standard way. Moreover, for every subgroup $\Gamma \subset \text{SL}_2(\mathbb{Z})$ of finite index, the quotient $X_\Gamma := \mathbb{H}^*/\Gamma$ carries a natural structure of a compact Riemann surface, and therefore also of a smooth projective curve over \mathbb{C} . The classical j -function identifies the quotient of \mathbb{H}^* by $\text{SL}_2(\mathbb{Z})$ with the projective line. So for each finite index subgroup Γ we obtain a finite cover of compact Riemann surfaces (or smooth projective curves over \mathbb{C})

$$f_\Gamma : X_\Gamma \longrightarrow \mathbb{P}^1.$$

This map is unramified away from the three points $0, 1728, \infty$. In other words, f_Γ is a three point cover.

For an integer N , let

$$\Gamma(N) := \{ A \in \text{SL}_2(\mathbb{Z}) \mid A \equiv I_2 \pmod{N} \}.$$

A *congruence subgroup* is a subgroup $\Gamma \subset \text{SL}_2(\mathbb{Z})$ which contains $\Gamma(N)$, for some N . The corresponding curve X_Γ is called a *modular curve*. The standard examples for congruence subgroups are $\Gamma(N)$, $\Gamma_0(N)$ and $\Gamma_1(N)$. The corresponding modular curves are usually denoted by $X(N)$, $X_0(N)$ and $X_1(N)$.

4.2. The modular curve $X(p)$.

Let us fix an odd prime number p . The three point cover $g : X(p) \rightarrow X(1) = \mathbb{P}^1$ is Galois, with Galois group $G = \text{PSL}_2(p)$. Its ramification index at the branch point ∞ (resp. at 0 , resp. at 1728) is equal to p (resp. 3 , resp. 2). Note that the order of G is equal to $p(p^2 - 1)/2$.

For technical reasons it is easier to discuss a variant of g , namely the three point cover

$$f : X(2p) \rightarrow X(2) = \mathbb{P}^1.$$

(We identify the modular curve $X(2)$ with \mathbb{P}^1 by means of the classical λ -function.) The cover f is Galois with Galois group $G = \text{PSL}_2(p)$. The

ramification index at each of the three branch points $0, 1, \infty$ is equal to p . There is an equivariant action of $\mathrm{SL}_2(2) \cong S_3$ on the source and the target of f . The cover g is obtained by taking the quotient under this action.

The next proposition follows easily from the results of [8].

Proposition 4.1. *The covers f and g can be defined over \mathbb{Q} . In particular, \mathbb{Q} is their field of moduli. Furthermore, g (resp. f) has good reduction at the prime l (in the sense of Definition 2.3) for $l \neq 2, 3, p$ (resp. for $l \neq p$).*

The fact that f and g can be defined over \mathbb{Q} follows also from the *rigidity criterion* used in inverse Galois theory. See [16] or [22]. The \mathbb{Q} -models of f and g are not unique. However, both covers have a unique model over the field $\mathbb{Q}(\sqrt{p^*})$ (where $p^* := (-1)^{\frac{p-1}{2}} p$).

Note that the second statement of Proposition 4.1 confirms (but is not implied by) the good reduction criterion discussed in §1.2. For $l = 2, 3$, the curve $X(p)$ has good reduction as well. However, since in this case l divides one of the ramification indices, the cover g has bad reduction – at least in the sense of Definition 2.3.

Since p exactly divides the order of G , the results discussed in §2 and §3 can be used to study the stable reduction of f and g at the prime p . This is done in detail in [4]. We shall present some of the main results of [4], as an illustration for the results discussed earlier.

Let K_0 be the completion of the maximal unramified extension of \mathbb{Q}_p . From now on, we consider the three points covers f and g as defined over K_0 . We remark that there are many different models of these covers over K_0 . However, the stable model, which exists over a finite extension of K_0 , is unique.

For simplicity, we discuss only the stable reduction of the cover f in detail. Let K/K_0 be the minimal extension over which f has semistable reduction, and let $\bar{f} : \bar{X} \rightarrow \bar{Y}$ denote the stable reduction of f . We will freely use the notation introduced in §2.3 and §2.4. Since f has bad reduction and p strictly divides the order of G , the conclusion of Theorem 2.4 holds. In particular, \bar{f} gives rise to a special deformation datum (\bar{Z}_0, ω_0) and to Galois covers $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$. Since all the ramification indices of the cover f are equal to p , none of the supersingular points $\lambda_i \in \bar{Y}_0 = \mathbb{P}_k^1$ equals $0, 1$ or ∞ . Moreover, the Galois covers \bar{f}_i are étale over $\bar{Y}_i - \{\lambda_i\}$.

Theorem 4.2.

- (1) *The field K is the (unique) tame extension of K_0 of degree $(p^2 - 1)/2$.*
- (2) *There are $r = (p - 1)/2$ supersingular points λ_i ; they are precisely the roots of the Hasse polynomial*

$$\Phi(t) = \sum_{j=0}^r \binom{r}{j}^2 t^j.$$

The Galois cover $\bar{Z}_0 \rightarrow \bar{Y}_0$ is the cyclic cover of degree r given by the equation $z^r = \Phi(t)$. Furthermore, we have $\omega_0 = z t^{-1}(t-1)^{-1}dt$.

- (3) For $i = 1, \dots, r$, the curve \bar{X}_i is given by the equation $y^{(p+1)/2} = x^p - x$. An element of $G = \text{PSL}_2(p)$, represented by a matrix $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{SL}_2(p)$, acts on \bar{X}_i as follows:

$$A(x) = \frac{ax + b}{cx + d}, \quad A(y) = \frac{y}{(cx + d)^2}.$$

For the proof of this theorem, see [4]. The main idea is this. One constructs a special G -map $\bar{f} : \bar{X} \rightarrow \bar{Y}$, which satisfies the conclusion of Theorem 4.2 (ii) and (iii). By Theorem 3.1, it lifts to a three point cover $f' : X' \rightarrow \mathbb{P}^1$, defined over the tame extension of K_0 of degree $(p^2 - 1)/2$. By the rigidity criterion of inverse Galois theory, f' has to be isomorphic to f . Whence the theorem.

One can prove a similar theorem about the stable reduction of $g : X(p) \rightarrow X(1) = \mathbb{P}^1$. If $p \equiv 1 \pmod{12}$ then the statements are almost identical, except that the Hasse polynomial has to be replaced by another polynomial (for which there is an explicit formula, similar to the expression for Φ). If $p \not\equiv 1 \pmod{12}$ then some of the supersingular points λ_i are equal to either 0 or 1728, and the corresponding Galois cover $\bar{f}_i : \bar{X}_i \rightarrow \bar{Y}_i$ is not the one from Theorem 4.2 (iii).

The modular curves $X_0(p)$, $X_1(p)$ and $X_0(p^2)$ are all quotients of the curve $X(p)$. Using the results of [4] on the stable reduction of $X(p)$, one can determine the stable reduction of all these quotients, reproving results of Deligne–Rapoport [8] and Edixhoven [9]. Somewhat surprisingly, this new proof does not use the interpretation of modular curves as moduli spaces for elliptic curves with level structure.

However, the ‘modular’ interpretation of modular curve justifies the use of the term ‘supersingular’ in §2.4 and §3.2. In fact, the supersingular points λ_i , which are the roots of the Hasse polynomial Φ , are exactly the values $t \in k$ for which the Legendre elliptic curve E_t with equation $y^2 = x(x-1)(x-t)$ is supersingular. Similarly, a point $t \in \mathbb{P}^1(K)$ lies in one of the open disks D'_i if and only if the elliptic curve E_t has supersingular reduction. The modular interpretation of the smaller closed disks $D_i \subset D'_i$ is somewhat less known. However, it can be shown (see e.g. [5]) that a point $t \in \mathbb{P}^1(K)$ lies in one of the disks D_i if and only if the elliptic curve E_t is *too supersingular*, which means that $E_t[p]$ has no canonical subgroup.

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