

Resolution of Singularities

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1 Introduction

For many of the most important theorems in mathematics giving even an approximate idea of what the theorem states is fairly hard. This is not the case with resolution of singularities. The basic idea is very geometric, and can be easily stated approximately assuming very little prior mathematics background. It is a statement considering varieties, i.e., solution sets of equation systems consisting entirely of polynomial equations.

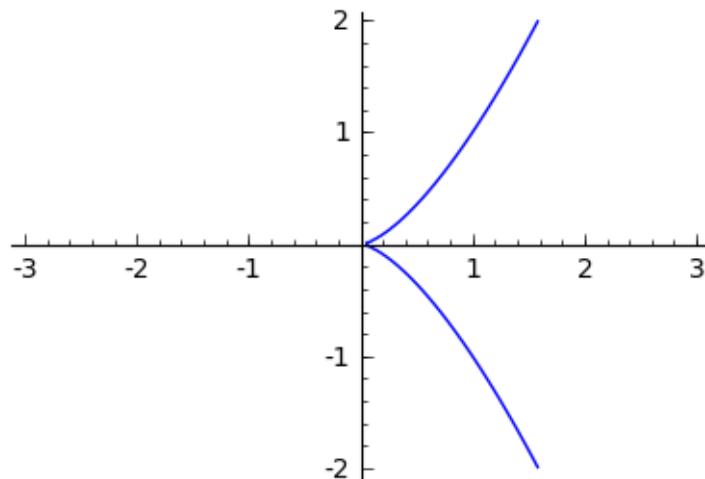


Figure 1: A cusp.

Let us start with an example. The solution set for the equation $y^2 - x^3$ is visualized in Figure 1. At every point of the curve, except at the origin, the curve seems to be smooth, i.e., if we zoom close enough, it starts looking like a straight line. These kind of points are called *nonsingular* or *regular points*. More generally in higher dimensional varieties (say the dimension is n) we would consider a point to be nonsingular if locally around it the variety looks like the "normal" n -dimensional space (you can think of \mathbb{R}^n if we are dealing with real solutions, \mathbb{C}^n if with complex solutions).

But something weird happens at the origin: the direction of the curve "changes" suddenly, and no matter how close we try to zoom, the curve will never start looking like a straight line. Points that fail to be nonsingular are called *singularities* or *singular points*. The type of curve singularity we have in Figure 1 is called a *cusp*.

Now a question arises: would it be possible to parametrize our singular curve C with another, nicer, curve: could we parametrize the points of C with points of a nonsingular curve C' (meaning that it has no singular points)? In the above case it is indeed possible. Take the curve C' that is the zero set of the polynomial equation $y'^2 - x'$ plotted in Figure 2. We would like to define a map $C' \rightarrow C$. Send a point $(x', y') \in C'$ to $(x', y'x')$. This point lies in C as

$$(y'x')^2 - x'^3 = x'^2(y'^2 - x'),$$

and the right hand side is zero by assumption. Hence we have what we desired: a parametrization of the curve C by a nonsingular curve C' .

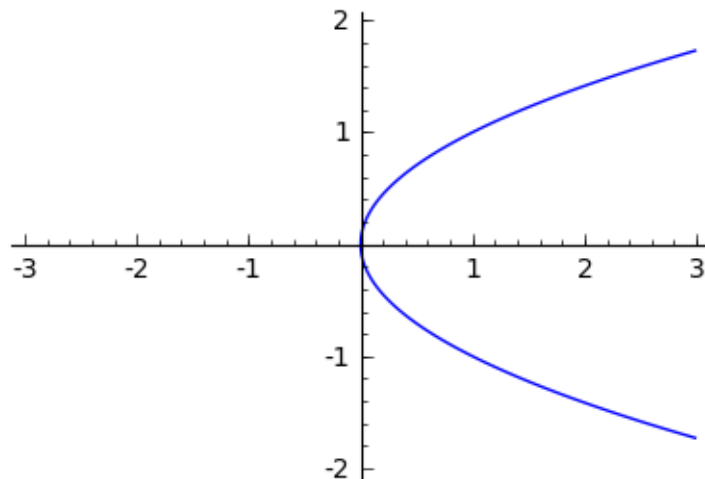


Figure 2: The solution set for $y'^2 - x' = 0$.

Before going further, let us have another example. The equation $y^2 - x^3 - x^2$ gives the curve visualized in Figure 3. The origin is clearly singular, but this singularity is different from the one we had in Figure 1. The curve intersects itself! Luckily this self-intersection is in some sense as good as possible, at least the different branches meet *transversally*, i.e., they have distinct tangent lines. A singular point, where two branches of a curve meet transversally is called a *node*.

Can we find a nonsingular parametrization for this curve? Yes we can. Take the curve $y'^2 - x' - 1$, which is visualized in Figure 4. A parametrization is again given by $(x', y') \mapsto (x', x'y')$ which can be checked with similar reasoning as before.

Finding a parametrization of a singular variety by a nonsingular one is called *resolving* its singularities (this is not what one usually means by it, usually we would require the parametrizing curve to be isomorphic to the original one almost everywhere). The problem of resolution of singularities simply asks whether or not the singularities of any variety can be resolved. It is also of some interest if there is a systematic way of doing this.

1.1 A condensed historical account of the problem

Although the problem is much older, we start with Oscar Zariski. Zariski was arguably the leading algebraic geometer of the first half of the twentieth century: if Grothendieck is to be regarded as the father of modern algebraic geometry, then Zariski is the grandfather. He did his undergraduate studies in Kiev, and later moved to do his doctorate in Rome

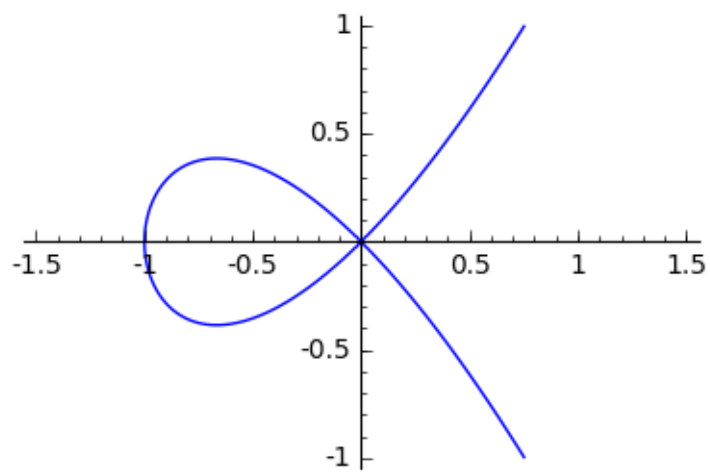


Figure 3: This kind of singularity is called a *node*.

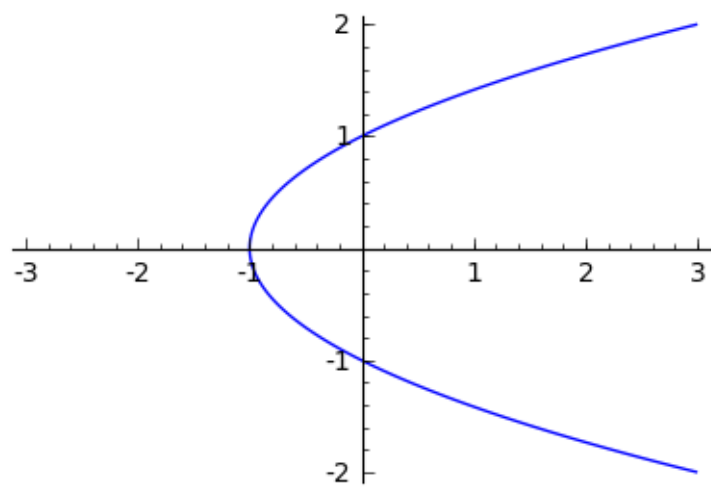


Figure 4: I swear, a parabola is not going to *always* work.

under Guido Castelnuovo. During his graduate studies he was very much influenced by what is now known as the Italian school of classical algebraic geometry, which is nowadays notorious for their usage of "geometric intuition" leading to some false proofs and untrue theorems.

But Zariski was more algebraically inclined than his Italian teachers. And even though he enjoyed the geometric way of thinking of the Italians, he also had some worries concerning their rigour. Because of these, Castelnuovo once stated: "Zariski, you are here with us but are not one of us" [Par]. This was not meant in a bad way, the methods of the Italian school had reached a dead-end, and would no longer be able to accomplish significant progress in the field, and Castelnuovo knew this all too well. But it would still take years before Zariski would start systematically rebuilding the foundations of algebraic geometry.

In 1932, now in the United States, Zariski began to work on his monograph *Algebraic Surfaces*, a task that would take him three years. The purpose of the monograph was to give a complete account of the results concerning algebraic curves obtained by the Italian school with rigorous proofs. However, while writing the book, he became increasingly certain that the entire foundations of algebraic geometry should be completely rebuilt using commutative algebra. He later stated himself: "working on that book took all my time because as I worked I became more and more disgusted with the kind of proofs that the Italian geometers were giving, and I started studying algebra seriously." [Par] He started incorporating recent results from commutative algebra achieved mainly by Noether, Krull and Dedekind, and casting everything in algebraic geometry in terms of the theory of commutative rings and their ideals.

After the completion of the monograph in 1935, Zariski went on to develop an abstract theory of algebraic geometry over an arbitrary (algebraically closed) ground field (instead of the coordinates of the points being complex numbers, they could be elements of some abstract field). It was during this time when he got interested in the resolution problem. The problem of resolution of singularities for higher dimensional varieties had long stood open, and many good mathematicians had given it a shot. Only some partial results had been achieved, and these were over complex numbers.

Zariski gave a simple proof for the resolution problem for surfaces using his notion of *normalization*, a term that should ring a bell to anyone who has studied algebraic geometry or commutative algebra. Resolution for surfaces is more complicated than for curves as the singularities of a surface need not to be confined in a finite set of points: the singular points can form curves as well. Normalizing a variety produces a variety whose singularities are of codimension two, which, in the case of surfaces, means that all singularities are point-singularities, i.e., the earlier complication is now gone! After normalization, resolving the singularities was fairly straightforward.

The resolution of singularities for surfaces had, however, essentially already been solved

by the Italian algebraic geometers [Par]. But Zariski didn't stop there. Later, he was able to show that the singularities of three-folds (three dimensional varieties) over a field of characteristic zero (three dimensional varieties) can be resolved. This was a problem that had completely eluded the approaches of the Italian school, and was also the moment that proved to rest of the world how powerful algebraic methods could be in algebraic geometry.

This is however where the contributions of Zariski (essentially) end. For further progress some time had to pass, and another rebuilding of the foundations of algebraic geometry had to happen. Alexander Grothendieck, motivated by the famous Weil conjectures linking together number theory and geometry, began a systematic rebuilding of the whole field in mid 50s. The result was a very powerful theory of algebraic geometry, whose level of abstraction was something previously unseen in mathematics. Even Mumford, a student of Zariski who won the Fields medal in 1974, stated the following in a letter to Grothendieck: "... I should say that I find the style of the finished works, esp. EGA, to be difficult and sometimes unreadable, because of its attempt to reach superhuman level of completeness." [Mum] One can only imagine the struggle for those mathematicians that weren't quite as good as Mumford when trying to learn the theory. Such was the power of this theory, however, that the theory became universally accepted rather quickly.

At the time, resolution of singularities was considered one of the most important open problems in algebraic geometry, for it would enable one to transfer many questions concerning singular varieties to questions involving only nonsingular ones, which are better understood. Even Grothendieck considered the problem to be one of the two most important ones, alongside his standard conjectures (which, to this day, remain open).

In the 60s Heisuke Hironaka, another student of Zariski to be given the Fields medal, decided to attack the resolution problem. Zariski himself never truly tried to deploy the Grothendieck style of algebraic geometry. This was probably because of the great time investment required in order to learn to use it, combined with the fact that his own research was going well enough. [Par] But Hironaka, like many of the students of Zariski, fully endorsed this new theory. With the new tools given by the theory of schemes, he was able to do what Zariski himself had tried and failed: in the famous paper published in 1964 in *Annals of Mathematics*, Hironaka gave a complete proof for resolution of singularities over a ground field of characteristic zero.

The proof, originally around 200 pages long, quickly gained a reputation for being extremely complicated and hard to understand. However, in further research the proof has been simplified and shortened considerably. For example in [Włó] Włodarczyk gives a self contained proof for resolution of singularities via a Hironaka-style argument in around twenty pages! An overview of a Hironaka-style argument for proof of resolution of singularities in characteristic 0 is given in Section 4.

This still left open the finite characteristic case important in many applications to

number theory. Partial results were obtained by Shreeram Abhyankar, another student of Zariski, who in 1966 published a proof for resolution of singularities for three-folds over algebraically closed fields of finite characteristic different from 2, 3 and 5 [HLOQ]. He later on went to generalize his result for three-folds in characteristic 2, 3 and 5, as well as giving a proof for resolution of singularities for arithmetic surfaces.

However, for a long time essentially no progress was made. Hironaka's argument resisted all attempts of generalization to finite characteristic, and all algebraic approaches in the spirit of Zariski and his students seemed to fail as well. The initial success of the algebraic approach had blinded almost the entire field into thinking that this was the right way. The spell was finally broken by a young Dutch mathematician Aise Johan de Jong, who in a 1995 talk gave an outline for a very geometric proof for resolving singularities by means of so called alterations.

His proof, published in a 1996 article [Jong], worked just as well over finite characteristic. A circle had closed: first algebra had had to replace geometry when geometrical methods failed, and now geometry, when all algebraic approaches seemed to fail, replaced algebra. Perhaps the most striking trait of his proof was the fact that essentially everything needed was already well known for nearly twenty years before the proof [HLOQ], the ingenious part was how the results were put together.

The resolution given by alterations is not, however, a resolution in the traditional sense. Traditionally one wants the resolution to produce a variety that is *birational* to the original variety, i.e., it is isomorphic to the original variety outside some small subset. What de Jongs method gives is more like some kind of finite cover. But for many of the applications this is enough. The traditional problem of resolution of singularities in finite characteristic remains open.

2 Completions

This section is devoted to an important construction called *completion* which, together with localization, forms a very powerful way of looking at the structure of an algebraic variety near a point. Familiarity with basic algebraic geometry and commutative algebra is assumed.

We begin with a motivating example. Recall the nodal curve C from the first section, defined as the solution set of the polynomial $y^2 - x^3 - x^2$. At the origin the curve intersects itself, and it seems like the curve should, at least near the origin, consist of two components. But as $y^2 - x^3 - x^2$ is an irreducible polynomial, the coordinate ring $\mathcal{O}_C(C)$ is an integral domain, as is the localization $\mathcal{O}_{C,p}$ at origin p .

This can be thought in the following way. The open sets of the Zariski topology are just the curve C minus finitely many points, so they contain almost all of the curve C .

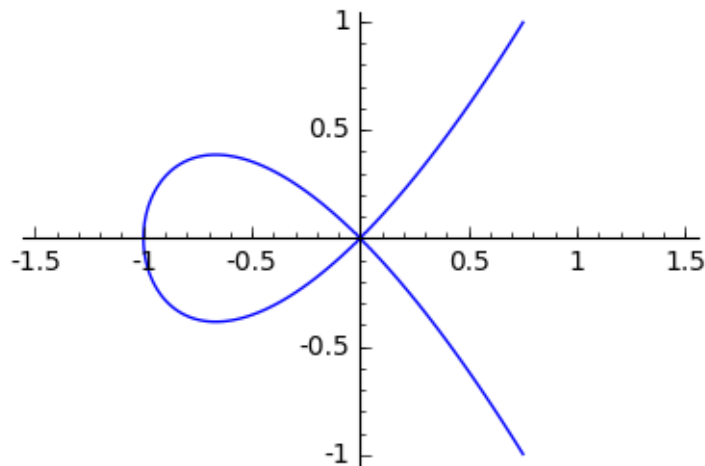


Figure 5: The nodal curve.

The localization at origin gives essentially all information about the curve C found in arbitrarily small neighbourhoods of the origin, and as none of these is small enough to make C irreducible, the localization stays irreducible. It is as if algebra doesn't allow us to see close enough.

Of course analytically we may break the curve into two branches: the equation of the curve

$$y^2 = x^3 + x^2$$

can be solved to give

$$y = \pm\sqrt{x^3 + x^2} = \pm x\sqrt{1 + x},$$

describing the two branches of the curve.

We may connect this back to algebraic geometry when we note that $\sqrt{1+x}$ can be expressed by its Taylor series. Hence, if we think $y^2 - x^3 - x^2$ as an element of the formal power series ring $k[[x, y]]$ instead of the polynomial ring $k[x, y]$, the equation $y^2 - x^3 - x^2$ cuts out a reducible subscheme of $\text{Spec} k[[x, y]]$, and the irreducible components correspond to the two branches at the origin. Somehow, when we passed into the ring of formal power series, we are now much closer to the origin than by localization.

As $k[[x, y]]$ is a local ring with maximal ideal (x, y) , the localization $k[x, y]_{(x, y)}$ embeds into it, and from this it is fairly easy to see that $\mathcal{O}_{C, p}$ embeds into $k[[x, y]]/(y^2 - x^3 - x^2)$. The idea of completion of local rings is exactly this: we want to get closer, so instead of just looking at the localization, we somehow replace the local ring with some sort of power series ring. We say that we pass into *formal neighbourhood* of a point p when we do this.

The nice thing is that these are usually much simpler than the local rings: for example, if we have a nonsingular k -variety X of dimension d , where k is algebraically closed, then the completion $\widehat{\mathcal{O}}_{X,p}$ of the local ring at a closed point p is isomorphic to $k[[x_1, \dots, x_d]]$.

2.1 Completion of topological abelian groups

Let G be a topological abelian group. We say that a sequence (x_i) in G is *Cauchy sequence* if for all neighbourhoods U of 0 we have $N_U \in \mathbb{N}$ such that $x_i - x_j \in U$ for all $i, j \geq N_U$. We say that G is *complete* if all Cauchy sequences converge to some value in G . Although this notion does make sense for non-Hausdorff groups too, from now on we will require complete groups to be Hausdorff.

Before continuing, we quickly recall the following useful fact of topological groups. If we set U_0 to be the intersection of all neighbourhoods of 0, then it is in fact true that U_0 is a subgroup of G . Moreover, this subgroup is closed, and it is zero if and only if G is Hausdorff. The topological group G/U_0 is Hausdorff and U_0 is contained in the kernel of any continuous homomorphism $G \rightarrow H$, where H is Hausdorff.

Definition 2.1. Let G be a topological abelian group. The (*Hausdorff*) *completion* of G , denoted by \widehat{G} , is "the smallest complete group where G can be mapped into". More precisely, this means that completion is a continuous group morphism $G \rightarrow \widehat{G}$, where \widehat{G} is complete, and for all continuous homomorphisms $G \rightarrow X$, where X is complete, we have a unique morphism such that the following diagram commutes:

$$\begin{array}{ccc} \widehat{G} & \overset{\exists!}{\dashrightarrow} & X \\ \uparrow & \nearrow & \\ G & & \end{array}$$

It is clear that this defines \widehat{G} up to unique isomorphism if it exists. Given a continuous homomorphism $f : G \rightarrow H$, the universal property induces a morphism $\widehat{f} : \widehat{G} \rightarrow \widehat{H}$, and it is easy to check that this defines a functor.

First property of the completion we are going to prove is the fact that it commutes with "passing into Hausdorffification".

Proposition 2.2. *Let G be a topological abelian group and U_0 the intersection of all neighbourhoods of 0. If the completion of G/U_0 exist, then $G \rightarrow G/U_0 \rightarrow \widehat{(G/U_0)}$ is the completion of G .*

Proof. Assume we have a morphism $G \rightarrow X$, where X is a complete topological group. As X is Hausdorff, we know that U_0 is contained in the kernel of our map, and we can find a unique morphism $G/U_0 \rightarrow X$ making the diagram

$$\begin{array}{ccc} & G/U_0 & \\ \uparrow & \text{---} \exists! \text{---} & \\ G & \xrightarrow{\quad} & X \end{array}$$

commute. We can now use the fact that the completion of G/U_0 is known to exist, and hence we have a unique map $\widehat{(G/U_0)} \rightarrow X$ making the upper triangle of

$$\begin{array}{ccc} G/U_0 & \xrightarrow{\quad} & \widehat{(G/U_0)} \\ \uparrow & \searrow & \vdots \exists! \\ G & \xrightarrow{\quad} & X \end{array}$$

commute. As $G \rightarrow G/U_0$ is surjective, the map $\widehat{(G/U_0)} \rightarrow X$ is also the only one making

$$\begin{array}{ccc} \widehat{(G/U_0)} & \text{---} \exists! \text{---} & X \\ \uparrow & \nearrow & \\ G & & \end{array}$$

commute, and hence we are done. \square

Next we will show that the completion always exists when G is first countable. The idea is exactly the same one that is used when completing metric spaces.

Denote by $s(G)$ the set of Cauchy sequences in group G . This is a group: if (x_i) is a Cauchy sequence, then so is $(-x_i)$ for negation is homeomorphism. If (x_i) and (y_i) are Cauchy sequences, then so is $(x_i + y_i)$. This is not too hard to see: for all neighbourhoods U of the origin, we have smaller neighbourhoods V_1 and V_2 such that $V_1 + V_2 \subset U$ by continuity of summation. Then we may choose N to be large enough so that $x_i - x_j \in V_1$ and $y_i - y_j \in V_2$ for all $i, j \geq N$. Now $(x_i + y_i) - (x_j + y_j) = (x_i - x_j) + (y_i - y_j) \in U$. Similarly we can see that $s_0(G)$, the sequences of G that converge to 0, is a subgroup of $s(G)$. We define a topological group G' algebraically as $s(G)/s_0(G)$.

Next we define G' topologically. For every neighbourhood U of 0, let $U' \subset G'$ consist of those equivalence classes $[(x_i)]$ for which there exists a neighbourhood ϵ of origin, such

that $x_i + \epsilon \subset U$ for $i \gg 0$. This is clearly independent of the choice of the representative (x_i) . This forms a neighbourhood basis for 0 in G' inducing a structure of a topological group, as the next lemma shows.

Lemma 2.3. *The open sets U' define a structure of a topological group on G' when we give G' the topology where the open sets are of form*

$$\{O \subset G' \mid \text{for all } x \in G' \text{ we have } U' \text{ s.t. } x + U' \subset O\}.$$

In this topology U' form a neighbourhood basis for 0 (we do not yet claim these to be open, although it is true).

Proof. From basic properties of topological groups, it suffices to show that the following three properties hold:

1. For all U', V' we have W' such that $W' \subset U' \cap V'$.
2. For all U' we have V' such that $V' + V' \subset U'$.
3. For all U' we have V' such that $V' \subset -U'$.

Verifying these conditions is fairly straightforward:

1. Here we may take $W = U \cap V$. For if $x \in W$, then for some ϵ we have that $x_i + \epsilon \subset W$ for i large enough, and hence also $x_i + \epsilon \subset U, V$ for such i .
2. Because G is a topological group, we may choose a neighbourhood V of the origin such that $V + V \subset U$. Assume $x, y \in V'$, so that we have ϵ such that the open sets $x_i + \epsilon$ and $y_i + \epsilon$ are contained in V for $i \gg 0$. But now $(x_i + \epsilon) + (y_i + \epsilon)$ is contained in U , and therefore $x' + y' \in U'$. This shows that $V' + V' \subset U'$.
3. Clearly we may choose $V = -U$.

This finishes the proof. □

Next we show the continuity of our homomorphism $G \rightarrow G'$.

Lemma 2.4. *The map $G \rightarrow G'$ defined earlier is continuous.*

Proof. It is enough to show continuity at the origin. This is shown if we show that the preimage of U' is U . It is clear that if $x \in G$ is not in U , then its image in G' does not lie inside U' . On the other hand, if $x \in U$, then by continuity of the addition, we see that we can find an open set ϵ containing 0 such that $x + \epsilon \subset U$. Hence the image of x lies in U' . □

We are getting ready to prove that $G \rightarrow G'$ is the completion. First, however, we note that the sets U' are actually open, and after that we are finally able to conclude that G' is complete.

Lemma 2.5. *The sets $U' \subset G'$ are open.*

Proof. Let $x \in U'$, i.e., we have an open set ϵ containing 0 such that $x_i + \epsilon \subset U$ for large i . Now I claim that $x + \epsilon' \subset U'$, which would finish the proof. If $y \in x + \epsilon'$, then we have an open neighbourhood δ of origin such that $y_i - x_i + \delta \subset \epsilon$ for large i . But as $y_i = (y_i - x_i) + x_i$, we see that for $i \gg 0$

$$\begin{aligned} y_i + \delta &= x_i + (y_i - x_i) + \delta \\ &\subset x_i + \epsilon \\ &\subset U, \end{aligned}$$

proving the claim. □

Lemma 2.6. *If G is first countable, then so is G' .*

Proof. If (U_i) is a countable open neighbourhood basis for $0 \in G$, then (U'_i) is a countable open neighbourhood basis for $0 \in G'$, proving the claim. □

Lemma 2.7. *Assume that G is first countable. Now every Cauchy sequence in G' converges.*

Proof. Let (U_i) and (U'_i) be as in the previous lemma. We may assume that U_i , and hence U'_i , are descending, i.e., $U_i \supset U_{i+1}$.

Let $(x^i)_i$ be a Cauchy sequence in G' . We can pass to a subsequence such that $x^{i_1} - x^{i_2} \in U'_n$ for $i_1, i_2 \geq n$, and to prove the convergence of the original sequence, it is enough to show that the new sequence converges. Each x^i is represented by some Cauchy sequence $(x^i_j)_j$ in G , we may pick representative such that $x^i_{j_1} - x^i_{j_2} \in U_n$ for all $j_1, j_2 \geq n$.

I claim that $(x^i)_i$ converges to the element x of G' represented by $x = (x^j_j)_j$. In order to show that this is indeed the case, we need to show that, for large i , we have $x^i - x \in U'_n$. Let i be such that $U_i + U_i + U_i + U_i \subset U_n$. Now for all $m \geq j \geq i$ we have

$$\begin{aligned} x^i_j - x^j_j &= (x^i_j - x^i_m) + (x^i_m - x^j_m) + (x^j_m - x^j_j) \\ &\in U_j + U_i + U_j \\ &\subset U_i + U_i + U_i, \end{aligned}$$

and hence, for large j , we have $x^i_j - x^j_j + U_i \subset U_n$, proving that $x^i - x \in U'_n$. This concludes the proof. □

Lemma 2.8. *The group G' is Hausdorff and if G is Hausdorff, then $G \rightarrow G'$ is a topological embedding.*

Proof. Let \mathcal{U} contain all the neighbourhoods of 0 in G . To prove that G' is Hausdorff, it is enough to show that $\bigcap_{U \in \mathcal{U}} U' = \{0\}$. If x lies in U' , for all its representatives (x_i) we have that $x_i \in U$ for large i . Hence if $x \in \bigcap_{U \in \mathcal{U}} U'$, then this means that x_i converges to 0, i.e., $x = 0 \in G'$.

If G is Hausdorff and $x \neq y$ are two of its elements, then $x - y$ is nonzero, and we have a neighbourhood U of the origin such that $x - y \notin U$. Therefore the images of x and y in G' cannot coincide, and we can conclude that $G \rightarrow G'$ is an injection.

Finally, we need to show that the map $G \rightarrow \text{im}(G)$ is a homeomorphism. But we have done the essential work already: by the proof of 2.4 it is clear that the image of an open neighbourhood U of the origin is just $U' \cap \text{im}(G)$. \square

Now we are finally ready to prove the existence of completion.

Theorem 2.9. *If G is first countable then $G \rightarrow G'$ is the completion of G .*

Proof. At least we know that G' is complete. Assume then that X is a complete topological group, and $f : G \rightarrow X$ a continuous homomorphism. It is clear by the definition of G' that its elements can be approximated by a sequences contained in the image of G . If we want to extend f into a continuous function $f' : G' \rightarrow X$, then for a point $x \in G'$ represented by a Cauchy sequence (x_i) in G , we must have that $f'(x) = \lim f(x_i)$. We are done if we can show that f' defined as above gives a well defined continuous morphism $G' \rightarrow X$.

First of all, as $f : G \rightarrow X$ is continuous, it is easy to see that it sends Cauchy sequences in G to Cauchy sequences in X . Hence at least the limit $\lim f(x_i)$ exists. If the Cauchy sequences (x_i) and (x'_i) define the same element of G , then $x_i - x'_i \rightarrow 0$, and thus $f(x_i) - f(x'_i) = f(x_i - x'_i) \rightarrow 0$. This proves that our map f' is a well defined function $G' \rightarrow X$. It is also easy to see that this is a homomorphism of groups. The final thing left is to show that f' is continuous.

Let $V \subset X$ be an open neighbourhood of 0. Let $0 \in V_2 \subset V$ be an open set such that $V_2 + V_2 \subset V$, and U_2 the preimage of V_2 in G . I claim that f' sends U'_2 into V . This is almost trivial: if x represented by (x_i) lies in U'_2 , then for large i , $x_i \in U_2$, and hence $f(x_i) \in V_2$. But from this it follows that $f(x_i) + V_2 \subset V$ for $i \gg 0$ and we can conclude, using the next lemma, that $f'(x) \in V$, which is exactly what we wanted. \square

Lemma 2.10. *If (x_i) is a convergent sequence in a topological abelian group G such that for some open set ϵ containing 0 $x_i + \epsilon \subset V$ for $i \gg 0$, then $x_i \rightarrow x \in V$.*

Proof. As $x_i \rightarrow x$, we must have $x - x_i \in \epsilon$ for large i , from which it follows that $x \in x_i + \epsilon \subset V$. \square

This general construction simultaneously takes care of, for example, completing rational numbers in the usual topology to obtain real numbers R_p , in the p -adic topology to obtain p -adic numbers \mathbb{Q}_p , completing $k[x_1, \dots, x_n]$ in a specific topology to obtain $k[[x_1, \dots, x_n]]$ and much more. We gather here some now trivial properties of the completion.

Corollary 2.11. *The completion of a discrete topological group G is G .*

Corollary 2.12. *Let H be a subgroup of first countable Hausdorff G . Now the closure of H in \widehat{G} is the completion of H .*

Proof. Now H is first countable and Hausdorff, and using the construction for the completion we just have described, the claim is trivial, as the closure of H in \widehat{G} is the set of points that can be approximated by sequences in H (\widehat{G} is first countable, otherwise this would not necessarily hold). \square

Filtrations

A special kind of topology often encountered in algebra is one given by *filtrations*. If G is a topological abelian group, then a filtration is just a descending chain

$$G = G_0 \supset G_1 \supset G_2 \supset \dots$$

of subgroups. The filtration induces a structure of a topological group, where G_i forms a neighbourhood basis for 0 (the argumentation is almost identical to 2.3). As the G_i are subgroups, for all $x \in G_i$ we have $x + G_i \subset G_i$, and therefore the sets G_i will be open in the topology.

G is necessarily first countable, and Hausdorff if and only if $\bigcap_i G_i$ is the trivial subgroup. Assuming this is the case, we can give another construction for the completion of G . It is based on the fact that for every equivalence class of Cauchy sequences, one can choose a representative (x_i) such that $x_i - x_j \in G_n$ for all $i, j \geq n$. Therefore x_i defines the following values up to G_i . Such sequences are clearly in one to one correspondence with elements of $\prod_i (G/G_i)$ where the higher coordinates agree with the i^{th} one modulo G_i . This is actually a special case of a general construction known as the *projective limit*. Usually this is denoted by $\varprojlim (G/G_i)$.

This construction is actually quite useful, as we shall see in a moment. Define a map $\Delta_G : \prod_i (G/G_i) \rightarrow \prod_i (G/G_i)$ by sending $([x_i])$ to $([x_i - x_{i+1}])$. The following proposition is just a restatement of the definition.

Proposition 2.13. *The limit $\varprojlim (G/G_i)$ is exactly the kernel of Δ_G .*

Using the above proposition, we can obtain some nice results rather easily using just a tiny bit of basic homological algebra. Namely:

Theorem 2.14. *Let H be a (topological) subgroup of G . Now we have a canonical isomorphism*

$$\varprojlim(\overline{G}/\overline{G_i}) \cong \varprojlim(G/G_i) / \varprojlim(H/H_i),$$

where $\overline{G} = G/H$, $\overline{G_i}$ is the image of G_i in \overline{G} , and $H_i = H \cap G_i$.

Proof. For each i , we clearly have the exact sequence

$$0 \rightarrow H/H_i \rightarrow G/G_i \rightarrow \overline{G}/\overline{G_i} \rightarrow 0$$

This gives rise to the following commutative diagram with exact rows:

$$\begin{array}{ccccccc} 0 & \longrightarrow & \prod_i(H/H_i) & \longrightarrow & \prod_i(G/G_i) & \longrightarrow & \prod_i(\overline{G}/\overline{H_i}) \longrightarrow 0 \\ & & \downarrow \Delta_H & & \downarrow \Delta_G & & \downarrow \Delta_{\overline{G}} \\ 0 & \longrightarrow & \prod_i(H/H_i) & \longrightarrow & \prod_i(G/G_i) & \longrightarrow & \prod_i(\overline{G}/\overline{H_i}) \longrightarrow 0 \end{array}$$

The snake lemma gives us the exact sequence

$$0 \rightarrow \varprojlim(H/H_i) \rightarrow \varprojlim(G/G_i) \rightarrow \varprojlim(\overline{G}/\overline{G_i}) \rightarrow \text{coker}(\Delta_H)$$

which proves our claim, as $\text{coker}(\Delta_H) = 0$ by the next lemma. \square

Lemma 2.15. *The map Δ_G is surjective.*

Proof. Let us have an element $x = (x_i) \in \prod_i(G/G_i)$. We construct an element $x' = (x'_i)$ that maps to x . Pick $x'_1 = x_1$ and $x'_2 = 0$, so that we have an element $(x'_1, x'_2, 0, 0, \dots)$ mapping to $(x_1, x_2, 0, 0, \dots)$.

Assume we have chosen $(x'_1, \dots, x'_{n+1}, 0, \dots)$ mapping to $(x_1, \dots, x_n, x'_{n+1}, 0, \dots)$. As the map $G/G_{n+2} \rightarrow G/G_{n+1}$ is surjective, we may choose x'_{n+2} in such a way that the difference $x'_{n+1} - x'_{n+2}$ equals x_{n+1} . But now $(x'_1, \dots, x'_{n+2}, 0, \dots)$ maps to $(x_1, \dots, x_{n+1}, x'_{n+2}, 0, \dots)$ and we are done by induction. \square

We have the following immediate corollary:

Corollary 2.16. *Let G be a topological group, whose topology is given by a filtration, and $H \leq G$ a subgroup. Now we have a canonical isomorphism*

$$\widehat{(\overline{G}/\overline{H})} \cong \widehat{G}/\widehat{H}.$$

Proof. This is a trivial consequence of the previous discussion. The fact that G is Hausdorff is used for identifying $\varprojlim(G/G_i)$ with the completion, and the fact that H is closed is necessary to make sure that G/H is Hausdorff. \square

This looks a bit like the completion might be exact, at least in good cases. But it is quite dangerous to try to think about these properties in that way: the category of topological abelian groups is not abelian as there is too much freedom in the choice of topology, and therefore one has to be quite careful when talking about exact sequences. This can, however, be fixed by restricting into a suitable subcategory which is restrictive enough on topology.

Quite often, a convenient way of specifying an element of \widehat{G} , where G has the topology induced by a filtration, is to give an infinite sum

$$\sum_i x_i$$

where $x_i \in G_i$. This is interpreted as the limit of the Cauchy sequence formed by the partial sums. It is clear that every element of the completion \widehat{G} can be expressed in this form.

2.2 Completions of topological rings and modules

A *topological ring* A is a topological abelian group with a continuous multiplication map $A \times A \rightarrow A$ satisfying the ring axioms. If A is a topological ring, then, quite naturally, a *topological A -module* is a topological abelian group together with a continuous multiplication $A \times M \rightarrow M$. We define the *completion* of a topological ring and a topological module to be the completion as a topological abelian group.

Using the constructions we have for completion, it is easy to see that if A is Hausdorff and first countable, then \widehat{A} is a topological ring, and similarly if M is Hausdorff and first countable, then \widehat{M} is both a topological A and a topological \widehat{A} -module.

If A is a ring (M an A -module), then a *filtration* on A (on M) is a descending sequence $I_1 \supset I_2 \supset \dots$ of ideals (descending sequence $M_1 \supset M_2 \supset \dots$ of submodules). Again, it is easy to see that filtration on A gives it a structure of a topological ring, and a filtration (M_i) on M satisfying $I_j M_i \subset M_{i+j}$ gives rise to a structure of a topological A -module.

The most common filtration occurring in commutative algebra is the *I -adic* filtration: we have an ideal I of A , and we set $I_i = I^i$. Similarly we have the *I -adic* filtration on M defined by $M_i = I^i M$. The induced topology is called the *I -adic topology*. Two well known theorems in commutative algebra can be given a topological meaning.

Proposition 2.17. (*Topological Krull's intersection theorem*) *Let A be a local Noetherian ring and I a proper ideal. Now the I -adic topology on A and on finite A -modules M is Hausdorff.*

Proof. The usual statement is that the intersection $\bigcap_i I^i M$ is zero, which is equivalent to the filtration inducing a Hausdorff topology. \square

Proposition 2.18. (*Topological Artin-Rees lemma*) *Let A be a Noetherian ring and I its proper ideal. Give the ring A the I -adic topology. If M is a finitely generated A -module with I -adic topology and N is a submodule of M , then the topology N inherits from M is exactly the I -adic topology.*

Proof. Again, the usual statement is just that the I -adic filtration on M restricts to a I -good filtration on N , which is easily seen to prove the claim. \square

Assume that the ring A is Noetherian. We can now restrict our attention to the category of finitely generated I -adic A -modules. The objects are just finitely generated A -modules with the I -adic topology and the morphisms are the continuous A -linear maps. However, if $f : M \rightarrow N$ is any map of A -modules, then $f(I^i M) \subset I^i N$, and hence the morphism is seen to be continuous in the I -adic topology. Hence, categorically, the finitely generated I -adic A -modules are equivalent to finitely generated A -modules. Especially we can conclude that they form an abelian category.

Now we can finally interpret the proof of 2.14 as saying that the completion is an exact functor. But for future use, it is convenient to note that the completion coincides with taking the tensor product with \widehat{A} . As the completion $M \rightarrow \widehat{M}$ is a map to a \widehat{A} -module, we have the usual map $\widehat{A} \otimes_A M \rightarrow \widehat{M}$. This is easily seen to define a natural transformation, which in good situations is an isomorphism.

Proposition 2.19. *Let A be a Noetherian ring and M a finitely generated A -module. Now the natural map $\widehat{A} \otimes_A M \rightarrow \widehat{M}$ is an isomorphism.*

Proof. This is clear if M is a free module. In the general case, as A is Noetherian, we know that M is *finitely presented*, i.e., we have an exact sequence

$$F_1 \rightarrow F_0 \rightarrow M \rightarrow 0$$

where the modules F_i are free. Using what we already know for free A -modules, we obtain the commutative diagram

$$\begin{array}{ccccccc} \widehat{A} \otimes_A F_1 & \longrightarrow & \widehat{A} \otimes_A F_0 & \longrightarrow & \widehat{A} \otimes_A M & \longrightarrow & 0 \\ \downarrow & & \downarrow & & & & \\ \widehat{F}_1 & \longrightarrow & \widehat{F}_0 & \longrightarrow & \widehat{M} & \longrightarrow & 0 \end{array}$$

where the vertical maps are isomorphisms. Now we can use the uniqueness of cokernels to conclude that the natural map $\widehat{A} \otimes_A M \rightarrow \widehat{M}$ is an isomorphism. \square

In the process we have seen that \widehat{A} is a flat A -algebra.

Proposition 2.20. *Assume that A is a Noetherian ring. Now the completion \widehat{A} is a flat A -algebra.*

Proof. As tensoring with \widehat{A} is the same as completion for all *finitely generated* A -modules, we see that $\widehat{A} \otimes_A$ preserves all short exact sequences of finitely generated A -modules. But it is well known that this is equivalent to \widehat{A} being flat. \square

From now on, assume that we are dealing with a local ring A with maximal ideal m_A and residue field $K = A/m_A$. Moreover, unless otherwise stated, all completions will be taken with respect to the m_A -adic topology.

Proposition 2.21. *The completion \widehat{A} is a local ring with maximal ideal \widehat{m}_A and residue field K .*

Proof. We know that $\widehat{A}/\widehat{m}_A \cong (\widehat{A/m_A})$ naturally, and as A/m_A is K with the discrete topology, the left hand side of the equation is K . This proves that \widehat{m}_A is a maximal ideal.

In order to see that it is the only one, we need to show that \widehat{m}_A contains all nonunits of \widehat{A} . This is perhaps most easily seen from the limit construction: the completion of m_A consists of exactly those elements of $\varprojlim (A/m_A^i)$, whose first coordinate is zero. If this is not the case, then in all coordinates we have something in A/m_A^i not lying in the image of m_A . But this means that the coordinates are units, and hence the element is invertible as well, proving that all elements lying outside \widehat{m}_A are units. \square

2.3 Hensel's lemma

One of the nicest property of complete rings is what is known as the Hensel's lemma. The version we are going to give states that if a polynomial $f \in A[x]$ has a simple root in A/m_A , then it also has a root in \widehat{A} .

Theorem 2.22. Hensel's lemma. *Let f be a polynomial in $A[x]$ which has a simple root $[a_0] \in A/m_A$. Now there is an element $a \in \widehat{A}$ such that $a = a_0$ modulo m_A and $f(a) = 0$.*

Proof. It is enough to find sums $a_0 + a_1 + \dots + a_n$, where $a_i \in m_A^i$, such that $f(a_0 + \dots + a_n) \in m_A^{n+1}$ for all n . This is because the polynomial f clearly defines a continuous map $A \rightarrow A$ and $f(a_0 + \dots + a_n) \rightarrow 0$ as n tends to infinity. Thus, if we set $a = a_0 + a_1 + \dots$, then $f(a) = 0$.

Assume we have already chosen a_0, \dots, a_n , and would like to choose $a_{n+1} \in m_A^{n+1}$ in a way that our inductive assumption would still hold. Now we have

$$f(a_0 + \dots + a_n + a_{n+1}) = f(a_0 + \dots + a_n) + f'(a_0 + \dots + a_n)a_{n+1} + ba_{n+1}^2$$

where $b \in A$. If we look at the right hand side in A/m_A^{n+2} , we obtain the following equation:

$$0 = f(a_0 + \dots + a_n) + f'(a_0 + \dots + a_n)a_{n+1}.$$

now $f'(a_0 + \dots + a_n) = f'(a_0) \neq 0$ in A/m_A , and hence $f'(a_0 + \dots + a_n)$ is invertible in A/m_A^{n+2} . We may now solve a_{n+1} from the equation:

$$a_{n+1} = -\frac{f(a_0 + \dots + a_n)}{f'(a_0 + \dots + a_n)},$$

and we are done by induction. \square

2.4 Structure of completions of local Noetherian rings

One of the great things about completion is how it simplifies the theory of local rings. Although localization tries to encapsulate only the local information near a point in a variety, it usually contains very much information, as the open sets of the Zariski topology are so large. Therefore the structure of the local rings is also quite varied. However, once we require completeness, the rings have surprisingly little structural freedom. In this subsection we concentrate on local k -algebras where k is a field of characteristic 0.

Lemma 2.23. *Let A contain a field of characteristic 0. Now \hat{A} contains a coordinate field, i.e., a field mapping isomorphically onto A/m_A in the quotient map $\hat{A} \rightarrow \hat{A}/\widehat{m_A} = A/m_A$.*

Proof. Clearly A contains a field of characteristic 0 if and only if it contains \mathbb{Q} . Denote by K the residue field A/m_A .

Let $(\alpha_i)_{i \in I}$ be a transcendence basis for K over \mathbb{Q} , i.e., a collection of elements of K satisfying no nontrivial algebraic relations over \mathbb{Q} such that K is algebraic over $\mathbb{Q}((\alpha_i)_{i \in I})$. Now we can clearly choose elements $a_i \in A$ such that $a_i = \alpha_i$ modulo m_A , and thus we see that $\mathbb{Q}((\alpha_i)_{i \in I}) \cong \mathbb{Q}((a_i)_{i \in I}) \subset A$. Hence $\mathbb{Q}((a_i)_{i \in I})$ is also contained in \hat{A} .

Now we may extend $\mathbb{Q}((a_i)_{i \in I})$ into K by using Hensel's and (if needed) transfinite induction. This works because if we have an intermediate field extension $\mathbb{Q}((a_i)_{i \in I}) \subset M \subset K$, then also M has characteristic 0, and hence any element of K is a simple root of a polynomial with coefficients in M , and hence can be lifted to \hat{A} by Hensel's lemma. \square

To make use of the previous result, we introduce a useful construction. Given a (not necessarily local) ring A , we can construct the *graded ring* associated to I -adic filtration, denoted by $\text{gr}_I(A)$ or just $\text{gr}(A)$, as follows: as an abelian group, it is just the direct sum $\bigoplus_{i=0}^{\infty} (I^i/I^{i+1})$. To define it as a graded ring, we simply note that the map $(I^i/I^{i+1}) \times (I^j/I^{j+1}) \rightarrow I^{i+j}/I^{i+j+1}$ induced by the multiplication of A is well defined.

Assume that we have a morphism of $f : A \rightarrow B$ of general commutative rings, and let us have ideals $I \subset A$ and $J \subset B$ such that $fI \subset J$. Now also $fI^i \subset J^i$, and therefore we may define a map $\text{gr}_I(A) \rightarrow \text{gr}_J(B)$ of graded rings.

Lemma 2.24. *Let us have a homomorphism $f : A \rightarrow B$ of rings, and ideals $I \subset A$ and $J \subset B$ be such that $fI \subset J$ and the induced map $A/I \rightarrow B/J$ is a surjection. If the image of I generates J over B , then the associated map $\text{gr}(A) \rightarrow \text{gr}(B)$ is surjective.*

Proof. It is enough to show that for all i , the degree i part of the associated map is surjective. The case $i = 0$ has already been taken care of as $A/I \rightarrow B/J$ was assumed to be surjective. By the assumption that fI generates J over B , we see that fI^i generates J^i over B . Hence the image of I^i/I^{i+1} generates J^i/J^{i+1} over B/J . But as J^i/J^{i+1} can be also thought as an A/I algebra, and as $A/I \rightarrow B/J$ is surjective, and finally as the associated map $I^i/I^{i+1} \rightarrow J^i/J^{i+1}$ is a map of (A/I) -modules, we see that the map $I^i/I^{i+1} \rightarrow J^i/J^{i+1}$ must be surjective. \square

Using the above lemma, we can prove an important theorem concerning the structure of completions.

Theorem 2.25. *Let A be a Noetherian local ring containing a field of characteristic 0. Now \widehat{A} is isomorphic to $K[[x_1, \dots, x_n]]/I$, where $K = A/m_A$.*

Proof. As A is Noetherian, the maximal ideal m_A is generated by a finite collection a_1, \dots, a_n of elements. Moreover the images of these elements in \widehat{A} generate the maximal ideal \widehat{m}_A . As K is contained in \widehat{A} , we get a map of rings $K[x_1, \dots, x_n] \rightarrow \widehat{A}$ which sends x_i to a_i . If we denote by I the ideal of $K[x_1, \dots, x_n]$ generated by all the x_i , then we can use the above lemma to see that the associated map $\text{gr}_I(K[x_1, \dots, x_n]) \rightarrow \text{gr}_{\widehat{m}_A}(\widehat{A})$ is surjective. But this means that $K[x_1, \dots, x_n]/I^i \rightarrow \widehat{A}/\widehat{m}_A^i$ is surjective for all i .

We notice that $\varprojlim (K[x_1, \dots, x_n]/I^i) = K[[x_1, \dots, x_n]]$ and $\varprojlim (\widehat{A}/\widehat{m}_A^i) = \widehat{A}$, and hence we are done using the next lemma. \square

Lemma 2.26. *Let $G \rightarrow H$ be a map of abelian groups with filtrations (G_i) and (H_i) respectively. Assume that the image of G_i is contained in H_i , i.e., that we have induced maps $G/G_i \rightarrow H/H_i$. If these induced maps are surjective, then so is the limit map $\varprojlim (G/G_i) \rightarrow \varprojlim (H/H_i)$.*

Proof. This is essentially proven in 2.14. \square

One of the nicer theorem concerning completions tells us, among other things, that if we have a regular point p on a variety X , then formally locally the variety looks like an affine space near the point p , i.e., $\widehat{\mathcal{O}}_{X,p} \cong K[[x_1, \dots, x_n]]$. Before proving this, however, we need a lemma.

Lemma 2.27. *Let A be a regular local ring of dimension d , $K = A/m_A$, and let m_A be generated by a regular sequence a_1, \dots, a_d . Now the associated graded ring is isomorphic to $K[x_1, \dots, x_d]$ via a map $K[x_1, \dots, x_d] \rightarrow \text{gr}_{m_A}(A)$ sending x_i to the image of a_i in m_A/m_A^2 .*

Proof. As a_i generate the maximal ideal of A , we see that the map $k[x_1, \dots, x_d] \rightarrow \text{gr}(A)$ is surjective (it is clear that $\text{gr}_I(k[x_1, \dots, x_d])$, where $I = (x_1, \dots, x_d)$, is just $k[x_1, \dots, x_d]$ with the usual grading). We need to show that this is an injection, which is equivalent to stating that for all nonzero homogeneous polynomials F we have $F(a_1, \dots, a_d) \neq 0$.

Assume that this is not the case, i.e., we have some nonzero homogeneous F of degree n such that $F(a_1, \dots, a_d) = 0$. We can lift the coefficients of F from K to A and obtain a homogeneous polynomial $\tilde{F} \in A[x]$ such that $\tilde{F}(a_1, \dots, a_d) \in m_A^{n+1}$. Thus for some homogeneous polynomial H of degree $n+1$, we have that $(\tilde{F} - H)(a_1, \dots, a_d) = 0$, i.e., we have a nontrivial algebraic relation, defined by a polynomial $f \in A[x]$ with no constant terms, among the a_i .

But this leads to a contradiction. If x_1 divides f , we are done, as a_1 is a zerodivisor. Otherwise we move to modulo a_1 and to a new polynomial $f(0, x_2, \dots, x_d)$. Then we do the same thing for a_2 and a_3 and so on, until we find that some a_i is a zerodivisor modulo a_1, \dots, a_{i-1} . This must happen at least when $i = d$, as the polynomial f had no constant terms. This concludes the proof. \square

Theorem 2.28. *Let A be a regular local ring of dimension d . Now there is an isomorphism $K[[x_1, \dots, x_d]] \xrightarrow{\sim} \hat{A}$, where $K = A/m_A$, and x_1, \dots, x_d is sent to an image of a regular sequence a_1, \dots, a_d generating m_A in \hat{A} .*

Proof. Let a_1, \dots, a_d be a regular sequence generating the maximal ideal m_A of A . By the previous lemma we have that the map $\text{gr}_I(K[x_1, \dots, x_d]) \rightarrow \text{gr}_{m_A}(A)$, where $I = (x_1, \dots, x_d)$, associated to the map sending x_i to a_i is an isomorphism. By dimensionality, we can therefore conclude that $K[x_1, \dots, x_d]/I^i \rightarrow A/m_A^i$ is an isomorphism for all i , which shows that the respective completions are isomorphic as well, proving the theorem. \square

3 Blowing Up

One of the most common ways of getting rid of singularities is called *blowing up*. The simplest case is blowing up a point on a plane, which we are going to introduce through an example now. Recall our old friend, the nodal curve, which has a singularity at the origin. We are going to get rid of the singularity by blowing up the origin.

We begin by mapping each point of the curve, except the origin, into a three dimensional space via the map that sends (x, y) to $(x, y, y/x)$. The z -coordinate is just the slope of the direct line connecting the point (x, y) with the origin.

When we embed the nodal curve, except of course the origin, this way into the affine three space \mathbb{A}^3 , the resulting space curve won't have any points on the locus $x = 0$. The points (x, y, z) belonging to the image satisfy two algebraic relations. First of all, they

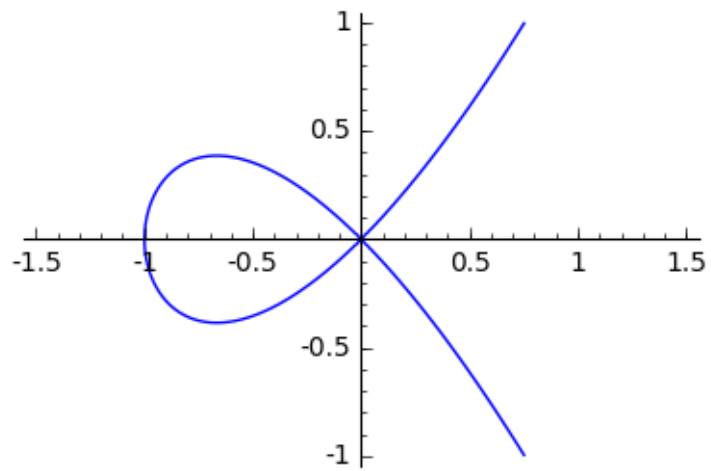


Figure 6: The nodal curve.

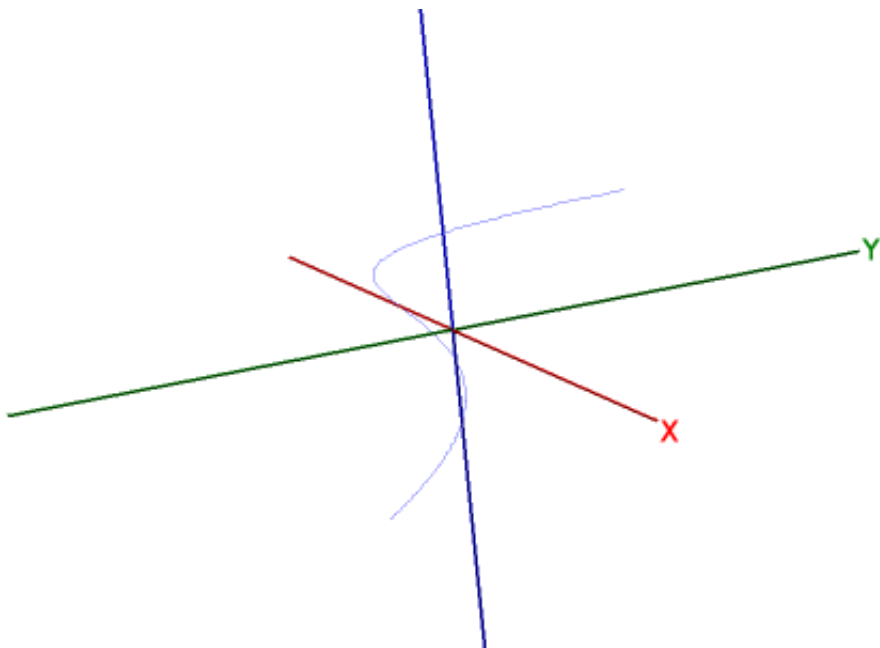


Figure 7: The Zariski closure of the image of nodal curve in affine 3-space.

must satisfy $y^2 - x^3 - x^2 = 0$ for this was the defining equation for the nodal curve. Secondly, we must have $zx = y$ because we sent the point (x, y) of the curve to $(x, y, y/x)$.

Any point of \mathbb{A}^3 having $x = 0$ and $y = 0$ satisfy the two algebraic relations we just mentioned, and in fact, if we denote by C' the set of points in \mathbb{A}^3 lying in the image of the nodal curve without origin, we can see that the two polynomial equations cut out exactly C' and the z -axis. We can do better. The *Zariski closure* $\overline{C'}$ of C' in \mathbb{A}^3 is the smallest subset of \mathbb{A}^3 that is given by some polynomial equation system and that contains C' . In this case it is the set of points cut out by $zx - y$ and $z^2 - x - 1$, and it is visualized in 7. Projection $\mathbb{A}^3 \rightarrow \mathbb{A}^2$ sending $(x, y, z) \rightarrow (x, y)$ maps the Zariski closure $\overline{C'}$ to the nodal curve C , and this mapping $\overline{C'} \rightarrow C$ is called the *blow-up*.

Outside the origin the preimage of a point of the nodal curve C is a single point in $\overline{C'}$, and the preimage of the origin consist of two points that correspond to the two branches. The blown up curve $\overline{C'}$ contains no singularities, so we have managed to resolve them. In this section, we are going to give the basic constructions and results of blow-ups.

3.1 Blowing up points in an affine space

Blowing up a point in an affine space \mathbb{A}^n is essentially very similar to what happened at the beginning of this section, although it is a bit more technical. We are only going to describe how to blow up the origin, the technique trivially generalizes to other points as well. From now on, unless otherwise stated, we work over an algebraically closed field.

The basic idea is to replace the origin with \mathbb{P}^{n-1} whose points corresponds to all the "tangent directions" at 0. We begin by taking the product space $\mathbb{A}^n \times \mathbb{P}^{n-1}$, whose coordinates we are going to denote by $(x_1, \dots, x_n, [u_1 : \dots : u_n])$. As we would like to have only the points of form $(x_1, \dots, x_n, [x_1 : \dots : x_n])$, we set the blown up space $\text{Bl}_0(\mathbb{A}^n)$ (where 0 stands for the fact that we blow up the origin) to be the closed subvariety of $\mathbb{A}^n \times \mathbb{P}^{n-1}$ cut out by equations $x_i u_j - x_j u_i = 0$. The first projection map clearly induces a morphism $\text{Bl}_0(\mathbb{A}^n) \rightarrow \mathbb{A}^n$ that is isomorphism outside the origin of \mathbb{A}^n . Over the origin we have the whole projective $(n-1)$ -space, so we have managed to do exactly what we wanted.

It is however more interesting to see what happens to *subvarieties* X of \mathbb{A}^n under the blow-up. The preimage of X in the map $\text{Bl}(\mathbb{A}^n) \rightarrow \mathbb{A}^n$ is called the *total transform* of X , and it is denoted by X^{tot} . The Zariski closure of the preimage of $X \setminus \{0\}$ in $\text{Bl}(\mathbb{A}^n)$ is called the *strict transform* X^{st} of X , and taking the strict transform is what is usually meant when we blow up a point on X . It is clear that the blow-up map $\text{Bl}(\mathbb{A}^n) \rightarrow \mathbb{A}^n$ restricts to give morphisms $X^{\text{tot}} \rightarrow X$ and $X^{\text{st}} \rightarrow X$.

Example 3.1. Lets get back to the example of the nodal curve C cut out of \mathbb{A}^2 by the polynomial $y^2 - x^3 - x^2$. We denote the points of the product variety $\mathbb{A}^2 \times \mathbb{P}^2$ by

$(x, y, [u : v])$, so the blown up plane $\text{Bl}(\mathbb{A}^2)$ is cut out by the polynomial $xv - yu$. Now the preimage of C in $\text{Bl}(\mathbb{A}^2)$ is cut out by furthermore requiring the equation $y^2 - x^3 - x^2$ to be satisfied. It is easy to see that if $(x, y) \neq (0, 0)$, then $(x, y, [x : y])$ is the only point of C^{tot} lying over it, and as every point of form $(0, 0, [u : v])$ is in C^{tot} , we see that the preimage of the origin is the whole \mathbb{P}^1 .

We can compute the strict transform of C locally. We pass to the locus where $u \neq 0$, so that we can parametrize the points by (x, y, z) where $z = v/u$. The part of the blown up plane lying here is cut out by $xz - y$. Now we notice that, as an algebraic variety, this is isomorphic to affine 2-space \mathbb{A}^2 by the map $(x, z) \mapsto (x, xz, z)$. The preimage of C minus the origin in this latter affine 2-space is the zero set of $x^2z^2 - x^3 - x^2$ outside the locus $x = 0$ (if $x = 0$, then also $xz = y$ is 0). The smallest algebraic set containing the preimage is the one cut out by $z^2 - x - 1$, because the resulting algebraic set must be one dimensional, and because the curve defined by the above equation is irreducible.

We conclude that in the first chart of $\mathbb{A}^2 \times \mathbb{P}^1$ the strict transform of C^{st} is cut out by the equations $xz - y$ and $z^2 - x - 1$, and hence the equations $xv - yu$ and $v^2 - (x + 1)u^2$ almost cut out the strict transform in $\mathbb{A}^2 \times \mathbb{P}^1$. As there may still be some extra points in the locus $u = 0$, we compute the strict transform in the second chart of $\mathbb{A}^2 \times \mathbb{P}^1$ and see that the equation $1 - yz^{-3} - z^{-2}$. Therefore we obtain one additional equation $v^3 - yu^3 - u^2v = 0$. Hence the strict transform $C^{st} \subset \mathbb{A}^2 \times \mathbb{P}^1$ is given by the equations

$$\begin{aligned} xv - yu &= 0 \\ v^2 - (x + 1)u^2 &= 0 \\ v^3 - yu^3 - u^2v &= 0. \end{aligned}$$

Example 3.2. The procedure given in the last example easily generalizes to computing the strict transformation of a hypersurface $X \subset \mathbb{A}^n$ when blowing up the origin. Let f be the defining polynomial for X , and let d be the degree of its lowest term. For the i^{th} chart of the $\mathbb{A}^n \times \mathbb{P}^{n-1}$ we get the relations

$$x_j = \frac{u_j}{u_i} x_i$$

and the polynomial $f(x_1, \dots, x_n)$ transforms into

$$f\left(\frac{u_1}{u_i} x_i, \dots, \frac{u_n}{u_i} x_i\right) = x_i^d \cdot g\left(\frac{u_1}{u_i} x_i, \dots, \frac{u_n}{u_i} x_i\right),$$

where g is not divisible by x_i . As the variety in question is isomorphic to \mathbb{A}^n with coordinates $x_i, u_1/u_i, \dots, u_n/u_i$, we can again conclude that the Zariski closure in the i^{th} chart is cut out by the polynomial g . Therefore one can compute the strict transform X^{st} of the hypersurface X simply by finding the local equations for all the n charts. Finding the strict transform of non-hypersurfaces is harder, as finding the Zariski closure is not as simple, not even locally.

Example 3.3. Assume that we have a plane curve C , cut out by polynomial f , and that the origin is a simple singularity of degree d . This means that at the origin we have d branches of the curve meeting transversally, i.e., their tangent lines are distinct. The lowest degree form F_{\min} of f factors into a linear product $\prod_i (a_i x_i - b_i y_i)$ and the lines defined by these linear factors are known to be exactly the tangent lines of the branches at the origin. Hence, the degree of the form is d , and the linear factors are pairwise different.

Blowing up this kind of singularity resolves it immediately. We break the polynomial f into a sum $F_d + F_{d+1} + \dots + F_n$ of its homogeneous parts, the reader should note that $F_d = F_{\min}$. We can see that the polynomial $x^{-d}f(x, xz)$ defining the strict transformation is now

$$F_d(1, z) + xF_{d+1}(1, z) + \dots + x^{n-d}F_n(1, z),$$

from which we see that the points of the strict transform C^{st} lying over the origin in the first chart are exactly the ones having $x = 0$ and z satisfying $F_d(1, z)$, which by assumption splits into *distinct* linear factors. As the intersection multiplicity with $x = 0$ is 1 at each of these points, we see that the points must be simple. In the other chart one does exactly the same things, and by symmetry we can conclude that all points lying over the origin in the strict transformation X^{st} are simple.

Example 3.4. A single blow-up may not be able to resolve the singularity even in the case of plane curves. Take the curve $y^2 - x^5 = 0$. The strict transform of in the first chart is cut out by $z^2 - x^3$, which has cusp at the origin. This could be resolved by blowing up the origin again (which we strictly speaking don't know how to do yet, because the strict transform is not necessarily contained in a affine space).

Example 3.5. Sometimes we cannot resolve a singular point no matter how many times we blow it up. The famous example of this is the *Whitney umbrella* which is an algebraic surface in \mathbb{A}^3 cut out by $x^2 - y^2z$. We compute the strict transform on the z -chart with coordinates x', y', z where $x = x'z$ and $y = y'z$, and see that it is cut out by the equation $z^{-2}(x'^2z^2 - y'^2z^3) = x'^2 - y'^2z$, which is essentially the same equation! Therefore blowing up the origin can never resolve the singularity. The singularity of the Whitney umbrella can however be resolved by blowing up, but instead of blowing up a point, we need to blow up the whole z -axis.

3.2 Blowing up simple subvarieties

In some cases it is very easy to see what *blowing up a subvariety* Y of \mathbb{A}^n should mean. Take for example the z -axis Z in \mathbb{A}^3 . We can think about \mathbb{A}^3 as an infinite family of affine 2-spaces parametrized by the z -coordinate, and we interpret blowing up the z -axis

(almost) just as blowing up the origin at each of these planes simultaneously. We end up with the blow-up map $\text{Bl}(\mathbb{A}^n) \times \mathbb{A}^1 \cong \text{Bl}_Z(\mathbb{A}^3) \rightarrow \mathbb{A}^3$. The strict and total transforms of subvarieties are defined similarly as before.

Example 3.6. We can now resolve the Whitney umbrella, which is cut out by $x^2 - y^2z$. The coordinates for $\text{Bl}_Z(\mathbb{A}^3)$ are $(x, y, z, [u : v])$, and the relation $xv - yu = 0$ is satisfied. On the first chart, we have

$$y = x \frac{v}{u},$$

and hence the defining equation can be transformed into

$$x^2 - x^2 \left(\frac{v}{u}\right)^2 z = x^2 \left(1 - \left(\frac{v}{u}\right)^2 z\right).$$

Therefore the first chart gives us the equation $u^2 - v^2z = 0$. Similarly we can calculate the strict transform in the second chart, but we get exactly the same equation from there. Hence the strict transform of the Whitney umbrella is the closed subvariety of $\mathbb{A}^3 \times \mathbb{P}^1$ cut out by the equations

$$\begin{aligned} xv - yu &= 0 \\ u^2 - v^2z &= 0. \end{aligned}$$

Moreover, we can see from the local equations that the strict transform is nonsingular, so we have managed to resolve the Whitney umbrella.

3.3 Blowing up, the general construction

Let X be a scheme and \mathcal{I} a sheaf of ideals (we require them to be quasicoherent and finite type) on X . The *blow-up of X along \mathcal{I}* , $\text{Bl}_{\mathcal{I}}(X)$, is defined as

$$\text{Proj}(\mathcal{O}_X \oplus \mathcal{I} \oplus \mathcal{I}^2 \oplus \dots),$$

where $\mathcal{O}_X \oplus \mathcal{I} \oplus \mathcal{I}^2 \oplus \dots$ is to be interpreted as a sheaf of graded algebras on X . From the basic properties of the global proj , we know that $\text{Bl}_{\mathcal{I}}(X)$ comes together with a canonical projection map $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$. If Y is a closed subscheme of X corresponding to a sheaf of ideals \mathcal{I} on X , then we define the *blow-up of X along Y* , $\text{Bl}_Y(X)$, to be $\text{Bl}_{\mathcal{I}}(X)$.

If $Z \subset X$ is a closed subscheme, then we define the *strict* and the *total transform* of Z under the blow-up $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ or $\text{Bl}_Y(X) \rightarrow X$ similarly as we did before.

Example 3.7. Our new notion coincides with the only one. Let's blow up the origin in an affine n -space \mathbb{A}_k^n . The coordinate ring for \mathbb{A}^n is just $A = k[x_1, \dots, x_n]$, and the origin corresponds to the ideal $I = (x_1, \dots, x_n)$. As we are working over an affine scheme, we

only need to show that $\text{Proj}(A \oplus I \oplus I^2 \oplus \dots)$ naturally corresponds to our earlier notion of blow-up.

Perhaps the easiest way to think about $A \oplus I \oplus I^2 \oplus \dots$ is to think it as the Rees-algebra $A[It] \subset A[t]$. This is a quotient of the graded A -algebra $A[y_1, \dots, y_n]$, where we assume that y_1, \dots, y_n have no algebraic relations amongst themselves, whose proj is just $\mathbb{P}_{\mathbb{A}^n}^{n-1}$, which in turn is naturally isomorphic to $\mathbb{A}^n \times_k \mathbb{P}_k^{n-1}$. Hence it is a closed subscheme of $\mathbb{A}^n \times_k \mathbb{P}_k^{n-1}$, as was our original definition.

What are the relations we must introduce between y_i in order to get the Rees-algebra $A[It]$? At least we must have $x_i y_j - x_j y_i = 0$, which are exactly the relations that cut the blow-up of our original definition. But are these relations enough this time? As it turns out, they are, which we are going to prove next.

Every polynomial $f \in A[y_1, \dots, y_n]$ can be broken into a sum

$$\sum_i c_i M_i(x_1, \dots, x_n) N_i(y_1, \dots, y_n),$$

where $c_i \in k$, and M_i, N_i are monomials. Image of each such term in $A[It]$ is of form

$$c M(x_1, \dots, x_n) N(x_1, \dots, x_n) t^{\deg(N)},$$

which is a monomial in $A[It] \subset k[x_1, \dots, x_n, t]$. For each such monomial in $A[It]$ we may collect all the summands, whose image corresponds to the same monomial up to multiplication by a scalar in k . All such terms are of form $c' M'(x_1, \dots, x_n) N'(x_1, \dots, x_n)$ such that

$$M'(x_1, \dots, x_n) N'(x_1, \dots, x_n) t^{\deg(N')} = M(x_1, \dots, x_n) N(x_1, \dots, x_n) t^{\deg(N)},$$

so if we form the sum of all these, we see that we obtain a polynomial F that is homogeneous as an element of $A[y_1, \dots, y_n]$ and has as coefficients monomials of $A = k[x_1, \dots, x_n]$. Moreover, it is also homogeneous as a polynomial in $k[x_1, \dots, x_n, y_1, \dots, y_n]$.

Assume now that f is a nonzero polynomial in the kernel of $A[y_1, \dots, y_n] \rightarrow A[It]$. Take some F formed by the above-mentioned procedure. We note that F must lie in the kernel as well, as different monomials in $A[It]$ are linearly independent, and the sum of all coefficients $c' \in k$ preceding the terms of the sum must be 0. We are done if we can show that F is zero modulo the relations $x_i y_j - x_j y_i$. But this is almost trivial. Using the relations $x_i y_j - x_j y_i$ we may transform all the terms in F into some scalar c' times $M(x_1, \dots, x_n) N(x_1, \dots, x_n)$. As the sum of the scalars must be 0, the sum thus obtained will be 0, and we are done.

If we blow up X along an ideal sheaf \mathcal{I} (along a subscheme Y) then nothing changes outside the cosupport of \mathcal{I} (outside Y).

Proposition 3.8. *Let us have a sheaf of ideals \mathcal{I} of a scheme X , and let $U = X \setminus \text{cosupp}(\mathcal{I})$. Now U is isomorphic to its preimage in the blow-up map.*

Proof. The cosupport of \mathcal{I} are exactly the points around which we have a neighbourhood V such that $\mathcal{I}|_V = \mathcal{O}_X|_V$. Hence it is easy to see that $\mathcal{I}|_U = \mathcal{O}_U$. Hence it is enough to prove that the blow-up of a scheme X along \mathcal{O}_X is X . But this is easy to do locally. If A is a ring, then the Rees-algebra $A[At]$ is just $A[t]$, and hence $\text{Proj}(A[t]) = A$ naturally along the projection map. As these local projection maps glue to give the global projection map, we are done. \square

For any morphism $f : X \rightarrow Y$ of schemes and every ideal sheaf $\mathcal{I} \subset \mathcal{O}_Y$ we have the *inverse image ideal sheaf* $f^{-1}\mathcal{I} \cdot \mathcal{O}_X$, which is the subsheaf of \mathcal{O}_X locally generated by the images of elements of $\mathcal{O}_Y(U)$ in $\mathcal{O}_X(f^{-1}U)$. It is not *a priori* clear that this satisfies our definition of an ideal sheaf, we still need to make sure that it is finitely generated and quasicohherent.

Proposition 3.9. *The sheaf $f^{-1}\mathcal{I} \cdot \mathcal{O}_X$ is quasicohherent and finitely generated.*

Proof. Let $U \subset Y$ and $V \subset f^{-1}U$ be affine open subschemes of Y and X respectively. Now the restriction of $f^{-1}\mathcal{I} \cdot \mathcal{O}_X$ is clearly generated by the image of $\mathcal{I}|_U$ in the map of rings $\mathcal{O}_Y(U) \rightarrow \mathcal{O}_X(V)$. Hence, locally, $f^{-1}\mathcal{I} \cdot \mathcal{O}_X$ is quasicohherent and finitely generated, and we are done. \square

An interesting property of the blow-up $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ along \mathcal{I} is the fact that the inverse image sheaf of \mathcal{I} is an invertible sheaf, i.e., locally it is generated by a single nonzerodivisor.

Proposition 3.10. *The inverse image sheaf of \mathcal{I} under the blow-up map $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ is invertible.*

Proof. By checking over all affine open $U \subset X$ we see that the ideal in question is the one given the subsheaf

$$\mathcal{I} \oplus \mathcal{I}^2 \oplus \mathcal{I}^3 \dots \subset \mathcal{O}_X \oplus \mathcal{I} \oplus \mathcal{I}^2 \dots$$

But the sheaf on $\text{Bl}_{\mathcal{I}}(X)$ given by this graded sheaf is exactly the first twisting sheaf $\mathcal{O}_{\text{Bl}_{\mathcal{I}}(X)}(1)$, which is known to be invertible. This proves the claim. \square

Moreover, blowing up along an invertible ideal sheaf doesn't change anything, so after we blow up along \mathcal{I} then blowing up along the inverse image ideal sheaf does nothing.

Proposition 3.11. *Let \mathcal{I} be an invertible sheaf of ideals on a scheme X . Now the blow-up morphism $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ is an isomorphism.*

Proof. Again, we only need to check this locally. For any open affine $U \subset X$ small enough that $\mathcal{I}|_U = I$ is principal and generated by a nonzerodivisor $a \in \mathcal{O}_U = A$, we see that the Rees-algebra $A[It] = A[at]$ is isomorphic to $A[t]$, reducing us to the case where $I = A$ already solved earlier. \square

The preimage of the cosupport of \mathcal{I} in the blow-up map $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ is called the *exceptional divisor* of $\text{Bl}_{\mathcal{I}}(X)$. As it is the subscheme cut out by the inverse image ideal sheaf of \mathcal{I} , it is truly a divisor, so the name is justified. Moreover, as the sheaf of ideals is locally generated by a single nonzerodivisor, dividing by it does make sense.

3.4 Transformations of sheaves of ideals

This section, although rather short, will be very important for us later, as it contains many important definitions. Let us have a scheme X and a blow-up map $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ along \mathcal{I} and let \mathcal{J} be an ideal sheaf. There are four ways to transform the ideal \mathcal{J} under blow-up:

- The *total transform* \mathcal{J}^{tot} of \mathcal{J} is just the inverse image ideal sheaf under the map $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$.
- The *strict transform* \mathcal{J}^{st} of \mathcal{J} is the ideal sheaf locally generated by images of elements of $\mathcal{O}_X(U)$ in $\mathcal{O}_{\text{Bl}_{\mathcal{I}}(X)}(U')$, where U' is the preimage of U , each divided by the inverse image ideal sheaf of \mathcal{I} as many times as they are divisible by it.

This clearly corresponds to the closure (in the algebro-geometric sense) of the closed subscheme defined by \mathcal{J}^{tot} minus the exceptional divisor in $\text{Bl}_{\mathcal{I}}(X)$, and is therefore at least quasicoherent. Over locally Noetherian schemes, however, it is also necessarily finitely generated, and as all schemes we actually work with are locally Noetherian, we see that this is an ideal sheaf.

- The *weak transform* \mathcal{J}^w is the inverse image ideal sheaf of \mathcal{J} under $\text{Bl}_{\mathcal{I}}(X) \rightarrow X$ divided as many times by the ideal sheaf of the exceptional divisor as many times as possible.
- The *controlled transform* \mathcal{J}^c is like the weak transform except we have the *control* (a positive integer) which limits the number of times we divide by the inverse image ideal sheaf of \mathcal{I} .

We also have the corresponding transforms for closed subschemes Y of X defined in the obvious way.

3.5 Isomorphism results

From our construction of blow-up it is trivial to see that it commutes with passing to an open subscheme, and this also works in the limit, i.e., when restricting to the localization at a point. In this section we are going to prove many similar results. First we show that blowing up commutes with passing to a closed subscheme.

Proposition 3.12. *Let X be a scheme, \mathcal{I} a sheaf of ideals, and let $Y \xrightarrow{i} X$ be a closed embedding corresponding to an ideal sheaf \mathcal{I} . Now there is a unique morphism $\mathrm{Bl}_{\mathcal{I}|_Y}(Y) \rightarrow \mathrm{Bl}_{\mathcal{I}}(X)$ making the square*

$$\begin{array}{ccc} \mathrm{Bl}_{\mathcal{I}|_Y}(Y) & \longrightarrow & \mathrm{Bl}_{\mathcal{I}}(X) \\ \downarrow & & \downarrow \\ Y & \hookrightarrow & X \end{array}$$

commute. Moreover, this map is a closed embedding.

Proof. It is enough to show this affine-locally, as by uniqueness the local maps must glue to give a global one. So assume that $X = \mathrm{Spec}(A)$, and that $Y = \mathrm{Spec}(A/J)$. Now the blow-ups correspond to the Rees-algebras $A[It]$ and $(A/J)[\bar{I}t]$, where \bar{I} is the image of I in A/J . There is the natural surjection of graded algebras $A[It] \rightarrow (A/J)[\bar{I}t]$ which defines a closed immersion $\mathrm{Bl}_{\bar{I}}(Y) \rightarrow \mathrm{Bl}_I(X)$, so we are left with the task of showing its uniqueness.

The uniqueness is easy to see locally on $\mathrm{Proj}(A[It])$. The requirement of commutativity ensures us that for any element a in A or any of its localization is uniquely determined. Let a_1, \dots, a_r generate I , $a \in I$ and let's look at $\mathcal{O}_{\mathrm{Proj}(A[It])}(D(at)) = (A[It]_{at})_0$. Its elements are of form

$$\frac{F(a_1t, \dots, a_rt)}{a^d t^d} = \frac{F(a_1, \dots, a_r)}{a^d},$$

where F is a homogeneous polynomial of degree d . Hence all the elements in $(A[It]_{at})_0$ lie in a localization of A , and their images are therefore uniquely determined. Therefore there is a unique morphism $\mathrm{Bl}_{\bar{I}}(Y) \rightarrow \mathrm{Bl}_I(X)$ over the map $Y \rightarrow X$, so we are done. \square

Similar result holds for the other direction.

Proposition 3.13. *Let X be a scheme, and let $Y \xrightarrow{i} X$ be a closed embedding. Let \mathcal{I} be an ideal sheaf on Y . Now there is a unique morphism $\mathrm{Bl}_{\mathcal{I}}(Y) \rightarrow \mathrm{Bl}_{i_*\mathcal{I}}(X)$ making the square*

$$\begin{array}{ccc}
\mathrm{Bl}_{\mathcal{J}}(Y) & \longrightarrow & \mathrm{Bl}_{i_*\mathcal{J}}(X) \\
\downarrow & & \downarrow \\
Y & \hookrightarrow & X
\end{array}$$

commute. Moreover, this map is a closed embedding.

Proof. Now $(i_*\mathcal{J})|_Y = \mathcal{J}$, so this immediately follows from the last proposition. \square

Another result in the same spirit concerns completion.

Proposition 3.14. *Let A be a local ring and let I be a proper ideal of A . Now there is a natural isomorphism*

$$\widehat{A[\widehat{I}t]} \cong \widehat{A[It]}$$

where the completion is taken with respect to m_A on the left hand side, and with respect to $A[It]m_A$ on the right hand side.

Proof. \square

4 Hironaka's Proof

5 de Jong's Proof

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