

Wiles' numerical criterion

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1 A brief sketch of the proof of Fermat's Last Theorem

1.1 Fermat's Last Theorem and the modularity conjecture

Theorem 1.1 (Fermat's Last Theorem). *There are no $a, b, c \in \mathbb{Z}$ with $abc \neq 0$ and $n \in \mathbb{N}, n \geq 3$ such that*

$$a^n + b^n = c^n.$$

This is equivalent to

Theorem 1.2. *There are no $a, b, c \in \mathbb{Z}$ with $abc \neq 0$ and a prime number $p \geq 5$ such that*

$$a^p + b^p = c^p.$$

Indeed, let $a^n + b^n = c^n$ be a solution of the Fermat equation where $n \geq 3$. In the latter case, n is always divided by a prime number ≥ 3 or by 4. We can then write $n = \tilde{p} \cdot m$ where $\tilde{p} \in \{4\} \cup \{p | p \text{ odd prime}\}$ and obtain

$$a^n + b^n = c^n \Leftrightarrow (a^m)^{\tilde{p}} + (b^m)^{\tilde{p}} = (c^m)^{\tilde{p}}.$$

The case $\tilde{p} = 4$ has been ruled out by Fermat himself and the case $\tilde{p} = 3$ was shown soon after, so any solution of the Fermat equation of exponent n induces a solution of the Fermat equation for some prime number $p \geq 5$.

One of the key breakthroughs in the proof of FLT was to consider the

Definition 1.3 (Frey-Hellegouarch-Curve). From a solution of the Fermat equation we can with little technical modifications obtain a triple (a, b, c) such that $a^p + b^p + c^p = 0$, $a \not\equiv -1 \pmod{4}$, $2 \nmid b$. Then define the elliptic curve

$$E_{a,b,c}: y^2 = x(x - a^p)(x + b^p).$$

The existence of such a curve contradicts several well-known conjectures (such as Serre's conjecture, cf. next section) and Frey therefore conjectured that such a curve couldn't exist. He suggested to prove this by associating a modular form to this curve and showing that this modular form couldn't exist. The key point in this strategy was the following

Theorem 1.4 (Modularity). *Every semistable elliptic curve over \mathbb{Q} is modular, i.e. there is a modular form f "associated" to E in a sense that will be made precise in the next sections.*

When Frey had the idea of using this to prove FLT, theorem 1.4 still was a conjecture. It was finally proved by Andrew Wiles and Richard Taylor in 1995. (In the years until 1999 the semistability condition could be removed, so that the theorem holds for all elliptic curves.)

1.2 Galois representations and modularity

Definitions Let A be a complete noetherian local ring with finite residue field k . A continuous group homomorphism

$$\rho: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(A)$$

is called a Galois representation, where $G_{\mathbb{Q}}$ is endowed with the Krull topology. By reducing to the residue field, we obtain the residual representation

$$\bar{\rho}: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(k),$$

where the topology on k is the discrete topology. A residual representation can have multiple lifts. Two such lifts ρ, ρ' are called equivalent if $\rho' = M\rho M^{-1}$ for $M \in \mathrm{GL}_2(A)$ s.t. $M \equiv \mathrm{id}_2 \pmod{\mathfrak{m}_A}$. An equivalence class of lifts of ρ_0 is called deformation of ρ .

Definition 1.5. A Galois representation ρ is **odd** if $\rho(c) = -1$ where c denotes the generator of $G_{\mathbb{Q}_{\infty}}$. Note that $G_{\mathbb{Q}_{\infty}}$ is canonically isomorphic to the decomposition subgroup associated to ∞ in $G_{\mathbb{Q}}$.

Definition 1.6. A Galois representation ρ is **unramified** at ℓ if the inertia group I_{ℓ} is contained in the kernel of ρ . Being **flat** is a condition of similar nature, though considerably more technical.

Galois representations for elliptic curves As it is very difficult to come from an elliptic curve to a modular form directly, Wiles chose an indirect way via Galois representations. For each elliptic curve E over \mathbb{Q} , we can associate a Galois representation as follows. Take the p -torsion subgroup $E[p]$ of E (i.e. the kernel of p -multiplication on E). It is well known that we can choose a generating system P, Q for $E[p]$ and obtain an isomorphism $E[p] \cong (\mathbb{Z}/p\mathbb{Z})^2$. As $\mathbb{Q}(E[p])$ is a Galois number field, it is not hard to see that we have a continuous Galois operation on $E[p]$, i.e. a morphism

$$\mathrm{Gal}(\mathbb{Q}(E[p])/\mathbb{Q}) \rightarrow \mathrm{GL}_2(\mathbb{Z}/p\mathbb{Z}).$$

Completely analogous, we can construct compatible morphisms for $E[p^n]$ and in the limit we obtain a map

$$\rho_{E,p}: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(\mathbb{Z}_p).$$

One can show that $\rho_{E,p}$ is continuous with respect to the p -adic topology, i.e. $\rho_{E,p}$ is a Galois representation.

Proposition 1.7. [CSS97, chapter 1, theorem 2.11] Let N_E be the conductor of E and $\rho_{E,p}$ the representation described above. Then

- $\det \rho_{E,p} = \chi_p$,
- $\rho_{E,p}$ is unramified at primes not dividing pN_E , and

- $\rho_{E,p}$ is odd.

If E is semistable and Δ_E its minimal discriminant, we can further conclude that for

$$\bar{\rho}_{E,p}: G_Q \rightarrow \mathrm{GL}_2(\mathbb{Z}/p\mathbb{Z})$$

the following equivalences hold.

- $\bar{\rho}_{E,p}$ is flat at $p \Leftrightarrow p \mid \mathrm{ord}_p(\Delta_E)$.
- For any prime $\ell \neq p$: $\bar{\rho}_{E,p}$ is unramified at $\ell \Leftrightarrow p \mid \mathrm{ord}_\ell(\Delta_E)$.

Galois representations for modular forms Now that we have seen how to associate a Galois representation to an elliptic curve, we want to do the same thing for a modular form. However, this is far more difficult and therefore beyond the scope of this thesis. The result that we need is that to a new cuspform f of weight 2 we can associate a p -adic Galois representation ρ_f [see DS07, section 9.5]. Now we can state Serre's conjecture that was mentioned in the introduction. Let

$$\rho: G_Q \rightarrow \mathrm{GL}_2(\mathbb{F}_p)$$

be a continuous, odd, irreducible Galois representation. Then there exists a cuspidal eigenform f such that

$$\rho \cong \rho_f.$$

Serre even gives detailed formulas that assert a certain weight and level for f . In the case of $\rho_{E_{a,b,c},p}$ it predicts level two and weight two, a contradiction because the space of weight 2 modular forms of level 2 is zero. That might be one of the reasons why Frey conjectured that they Frey curve $E_{a,b,c}$ couldn't exist.

Modularity A Galois representation ρ is modular if there is a newform f of weight 2 such that

$$\rho \cong \rho_f.$$

For elliptic curves E/\mathbb{Q} we have the following definition/theorem.

Theorem 1.8. [CSS97, chapter 1, theorem 5.1] *An elliptic curve E/\mathbb{Q} with conductor N_E is modular if it satisfies the following equivalent conditions.*

1. For some prime p , $\rho_{E,p}$ is modular.
2. For all primes p , $\rho_{E,p}$ is modular.
3. There is a newform f of weight 2 and level N_E s.t. $L(f, s) = L(E, s)$.
4. There is a non-constant morphism $\pi: X_0(N_E) \rightarrow E$ of algebraic curves over \mathbb{Q} .
5. There is an isogeny $E \rightarrow A_f$, where A_f is the modular abelian variety associated to a weight 2 newform f of conductor N_E .

The last three equivalences are of no further relevance to the thesis but might be of interest to the reader.

1.3 Ribet's theorem and the contradiction

For a moment, let's believe that every semistable elliptic curve is modular. In order to prove FLT, we need one more deep ingredient, namely

Theorem 1.9 (Ribet's theorem). *Let f be a newform of weight 2 and level $N\ell$ for a prime ℓ s.t. $\ell \nmid N$. Suppose that the associated Galois representation $\bar{\rho}_f$ is absolutely irreducible and satisfies one of the following conditions.*

- $\bar{\rho}_f$ is unramified at ℓ
- $\ell = p$ and $\bar{\rho}_f$ is flat at p .

Then there is a newform of weight 2 and level N such that

$$\bar{\rho}_f \cong \bar{\rho}_g.$$

By modularity (cf. theorem 1.8) we find a newform f of weight 2 such that

$$\bar{\rho}_{E_{a,b,c,p}} \cong \bar{\rho}_f$$

We need the semistability of $E_{a,b,c}$ and the properties shown in proposition 1.7. Because of the specific properties of the Frey curve we have the following finer results for $\rho_{E_{a,b,c,p}}$ [see CSS97, chapter 1, theorem 3.1].

- $\rho_{E_{a,b,c,p}}$ is absolutely irreducible
- $\rho_{E_{a,b,c,p}}$ is unramified outside $2p$ and flat at p

As E is semistable, the conductor is squarefree,

$$N_E = 2 \cdot p \cdot \prod_{\ell \in S} \ell$$

for a finite set S of primes $\neq 2, p$. Let $\ell_0 \in S$. As $\bar{\rho}_{E_{a,b,c,p}}$ is unramified at ℓ_0 , by Ribet's theorem we find a newform f' of weight 2 and level

$$2 \cdot p \cdot \prod_{\ell \in S \setminus \{\ell_0\}} \ell$$

such that $\bar{\rho}_{f'} \cong \bar{\rho}_{E_{a,b,c,p}}$. By repeating this step, we obtain a newform g' of weight 2 and level $2p$ whose reduced Galois representation is still equivalent to $\bar{\rho}_{E_{a,b,c,p}}$. As $\bar{\rho}_{E_{a,b,c,p}}$ is flat at p , we find a newform g of weight 2 and level 2 such that

$$\bar{\rho}_{E_{a,b,c,p}} \cong \bar{\rho}_g.$$

However, the only newform of weight 2 and level 2 is 0, so we obtain the desired contradiction.

1.4 Wiles' proof: A modularity lifting theorem

What remains now for the proof of FLT is the proof of the modularity theorem, i.e. that every semistable elliptic curve is modular. The goal of this section is to sketch the proof of a theorem that allows us to deduce modularity for a Galois representation from modularity of its reduction. In this and in the next section, we follow [CSS97, chapter 1, §7].

Let K be a finite extension of \mathbb{Q}_ℓ and \mathcal{O} its ring of integers with residue field k . Then define the category $\mathcal{C}_{\mathcal{O}}$ as the category of local complete noetherian \mathcal{O} -algebras with residue field k (cf. section 2.2). Let

$$\bar{\rho}: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(k)$$

be a reduced Galois representation satisfying the conditions

- (A) $\det \bar{\rho}_{E,p} = \chi_p$
- (B) $\bar{\rho}_{E,p}$ is semistable
- (C) $\bar{\rho}_{E,p}$ is absolutely irreducible
- (D) $\bar{\rho}_{E,p}$ is modular, and $\bar{\rho}_{E,p}|_{G_{\mathbb{Q}}(\sqrt{-3})}$ is absolutely irreducible

The goal of this part of the proof is to show that all $\bar{\rho}$ -deformations

$$\rho: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(\mathcal{O})$$

of type Σ are modular (this is known as modularity lifting).

Definition 1.10. [see CSS97, chapter 1, paragraph 7.2] We say that a deformation ρ of $\bar{\rho}$ is of type Σ , if

- $\det \rho = \chi_p$
- ρ is unramified outside $S \cup \{p\} \cup \Sigma$ where S may denote the set of ramified places of $\bar{\rho}$
- ρ is semistable outside Σ
- if $p \notin \Sigma$ and $\bar{\rho}$ is flat at p , then ρ is flat at p .

The universal deformation ring Consider the functor

$$\mathcal{R}_{\Sigma}: \mathcal{C} \rightarrow \mathbf{FiniteSets}$$

that sends $A \in \mathcal{C}$ to the set of deformations of $\bar{\rho}$ of type Σ . Deformation theory by Mazur tells us that this functor is representable and we denote the representing object as R_{Σ} . Furthermore, we have the existence of a universal representation

$$\rho_{\Sigma}^{\mathrm{univ}}: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(R_{\Sigma}).$$

such that we obtain a 1:1 correspondence

$$\mathrm{Hom}(R_\Sigma, R) = \{\text{deformations } \rho: G_\mathbb{Q} \rightarrow \mathrm{GL}_2(R) \text{ of type } \Sigma\}$$

by sending $\phi: R_\Sigma \rightarrow R$ to the composition $\phi \circ \rho_\Sigma^{\mathrm{univ}}: G_\mathbb{Q} \rightarrow \mathrm{GL}_2(R)$.

Let f be a cuspidal eigenform f over K . Regard K as a subfield of $\overline{\mathbb{Q}}_\ell$ via a fixed embedding $\mathbb{Q} \subset \overline{\mathbb{Q}}_\ell$. Let the field K'_f denote the K -algebra in $\overline{\mathbb{Q}}_\ell$ generated by the Fourier coefficients of f and \mathcal{O}'_f its ring of integers. Define

$$\tilde{\mathbb{T}}_\Sigma = \prod_{f \in \mathcal{N}_\Sigma} \mathcal{O}'_f,$$

where \mathcal{N}_Σ is a finite set of newforms satisfying certain conditions [see DDT95, lemma 3.26]. For all but finitely many primes (e.g. $p \in \Sigma$ is not allowed), we define

$$T_p = (a_p(f))_f \in \tilde{\mathbb{T}}_\Sigma.$$

Finally we can define \mathbb{T}_Σ as the \mathcal{O} -algebra of $\tilde{\mathbb{T}}_\Sigma$ generated by the T_p . It can be shown [cf. DDT95, lemma 3.27] that

$$\rho_\Sigma^{\mathrm{mod}} := \prod_{f \in \mathcal{N}_\Sigma} \rho_f: G_\mathbb{Q} \rightarrow \mathrm{GL}_2(\mathbb{T}_\Sigma)$$

is a Galois representation with the following properties.

- $\rho_\Sigma^{\mathrm{mod}}$ is a lift of $\bar{\rho}$ of type Σ .
- There is a unique surjection $\phi_\Sigma: R_\Sigma \twoheadrightarrow \mathbb{T}_\Sigma$ s.t. $\rho_\Sigma^{\mathrm{mod}} \cong \phi_\Sigma \circ \rho_\Sigma^{\mathrm{univ}}$.
- Given a Galois representation $\rho: G_\mathbb{Q} \rightarrow \mathrm{GL}_2(\mathcal{O})$ of type Σ and a morphism

$$\phi: \mathbb{T}_\Sigma \rightarrow \mathcal{O}$$

s.t. $\phi \circ \rho_\Sigma^{\mathrm{mod}} = \rho$, it follows that ρ is modular.

R = T and the numerical criterion In order to show that $R_\Sigma \cong \mathbb{T}_\Sigma$ for all Σ , we need a special argument for $\Sigma = \emptyset$. However, from then on we can continue by an induction argument that mainly consists of computing the cardinality of some invariants and then applying Wiles' numerical criterion. This criterion tells us that if a certain inequality is satisfied, the surjection $R_\Sigma \twoheadrightarrow \mathbb{T}_\Sigma$ is an isomorphism (cf. proposition 2.55).

Proof of modularity lifting Consider a representation $\rho: G_\mathbb{Q} \rightarrow \mathrm{GL}_2(\mathcal{O})$ and its reduction $\bar{\rho}$. Suppose that $\bar{\rho}$ satisfies properties A - D from lemma 1.11. By the universal property of R_Σ we get an \mathcal{O} -algebra morphism ϕ and because we know that $R_\Sigma = \mathbb{T}_\Sigma$, we obtain

$$\mathbb{T}_\Sigma \xrightarrow[\sim]{\phi_\Sigma^{-1}} R_\Sigma \xrightarrow{\phi} \mathcal{O}$$

s.t. $\phi \circ \phi_\Sigma^{-1} \circ \rho_\Sigma^{\mathrm{mod}} = \rho$. Because of the third property of \mathbb{T}_Σ stated above, one can now deduce that ρ must be modular and the modularity lifting theorem follows.

1.5 Wiles' proof: The 3-5 trick

In order to finish the proof of the modularity theorem, we now need to show that the equivalence class of the Galois representation $\bar{\rho}_{E,p}$ associated to an elliptic curve E is a deformation of type Σ of its reduction $\bar{\rho}$.

Lemma 1.11. *There is a prime p such that the mod p reduction of the Galois representation $\rho_{E,p}$*

$$\bar{\rho}_{E,p}: G_{\mathbb{Q}} \rightarrow \mathrm{GL}_2(\mathbb{F}_p)$$

satisfies the following properties.

- (A) $\det \bar{\rho}_{E,p} = \chi_p$
- (B) $\bar{\rho}_{E,p}$ is semistable
- (C) $\bar{\rho}_{E,p}$ is absolutely irreducible
- (D) $\bar{\rho}_{E,p}$ is modular, and $\bar{\rho}_{E,p}|_{G_{\mathbb{Q}}(\sqrt{-3})}$ is absolutely irreducible

Proof. We have seen in proposition 1.7 that $\rho_{E,p}$ has determinant χ_p . As E is semistable we know that $\rho_{E,p}$ is semistable. We now need to prove that there is a p s.t. $\bar{\rho}_{E,p}$ is irreducible and modular. In fact, it can be shown that once irreducibility and modularity are clear, all conditions A-D hold. Wiles proved the following

Proposition 1.12. *Let E/\mathbb{Q} be a semistable elliptic curve. Then at least one of $\bar{\rho}_{E,3}$ or $\bar{\rho}_{E,5}$ is irreducible.*

This allows us to make a case distinction.

- If $\bar{\rho}_{E,3}$ is irreducible, then by some group theoretical considerations we can apply the Langlands-Tunnel-theorem and conclude that $\bar{\rho}_{E,3}$ is modular.
- If $\bar{\rho}_{E,5}$ is irreducible, then Wiles has shown that there is another semistable elliptic curve E'/\mathbb{Q} s.t. $\bar{\rho}_{E',3}$ is irreducible and $\bar{\rho}_{E',5} \cong \bar{\rho}_{E,5}$. Hence, we can apply the first case for E' and obtain that $\bar{\rho}_{E',3}$ is modular. However, by modularity lifting $\rho_{E',3}$ is modular and by theorem 1.8 then $\rho_{E',5}$ is modular. Therefore its reduction $\bar{\rho}_{E',5}$ and also the equivalent representation $\bar{\rho}_{E,5}$ are modular.

In either case we have found a p s.t. $\bar{\rho}_{E,p}$ is irreducible and modular. \square

By modularity lifting all deformations of type Σ are modular. As the equivalence class of a Galois representation associated to a semistable elliptic curve satisfies the conditions required to be of type Σ , we conclude that the Galois representations associated to a semistable elliptic curve is modular.

2 Wiles' numerical criterion

2.1 Introduction

Wiles has discovered a criterion for two rings in a specific category to be isomorphic that only depends on some numerical invariants of these rings. The aim of this section is to prove that criterion in its purely algebraic form. In our presentation, we closely follow [DDT95, sections 5.1 - 5.8].

2.2 Preliminaries and examples

Let \mathcal{O} be the ring of integers of a finite extension K of \mathbb{Q}_ℓ . As K is a local field, its ring of integers is a discrete valuation ring (DVR), i.e. \mathcal{O} is a local, noetherian Dedekind ring with maximal ideal λ . It is complete with respect to the λ -adic topology, a principal ideal domain (PID) and has residue field $k := \mathcal{O}/\lambda$. \mathbb{Z}_ℓ is the ring of integers of \mathbb{Q}_ℓ and $\mathbb{F}_\ell = \mathbb{Z}_\ell/\ell\mathbb{Z}_\ell$ its residue field. As K/\mathbb{Q}_ℓ is a finite extension, the residue field k of \mathcal{O} is a finite extension of \mathbb{F}_ℓ and therefore finite.

The categories $\mathcal{C}_\mathcal{O}$ and $\mathcal{C}_\mathcal{O}^\bullet$ In this section, we will mostly deal with very specific rings. Therefore we define the category $\mathcal{C}_\mathcal{O}$ where objects of $\mathcal{C}_\mathcal{O}$ are local complete noetherian \mathcal{O} -algebras with residue field k and the morphisms are local \mathcal{O} -algebra morphisms. Often, we even need some extra structure. We obtain the category $\mathcal{C}_\mathcal{O}^\bullet$ from $\mathcal{C}_\mathcal{O}$ by equipping an object A with an additional surjective \mathcal{O} -algebra homomorphism

$$\pi_A: A \twoheadrightarrow \mathcal{O},$$

the so-called augmentation map. The morphisms in $\mathcal{C}_\mathcal{O}^\bullet$ are local \mathcal{O} -algebra morphisms that respect the augmentation map structure, i.e. for a morphism $f: A \rightarrow B$ we have the commutative diagram

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ \pi_A \searrow & & \swarrow \pi_B \\ & \mathcal{O} & \end{array}.$$

In order to state Wiles' criterion, we need some more definitions.

Definition 2.1. $A \in \mathcal{C}_\mathcal{O}$ is called *finite flat*, if A is finitely generated and torsion-free as an \mathcal{O} -module. Note that \mathcal{O} is a PID and therefore being torsion-free is equivalent to being flat as an \mathcal{O} -module.

Definition 2.2 (complete intersection). [see DDT95, Def. 5.1] A finite flat ring $A \in \mathcal{C}_\mathcal{O}$ is called a *complete intersection*, if A is isomorphic as an \mathcal{O} -algebra to a quotient

$$A \cong \mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n),$$

where there are as many relations as there are variables.

Let's take a look at an example.

Example 2.3. [cf. DDT95, example 1] $A = \{(a, b) \in \mathcal{O} \times \mathcal{O}, a \equiv b \pmod{\lambda^n}\} \cong \mathcal{O}[[T]]/(T(T - \lambda^n))$ is a finite flat complete intersection in $\mathcal{C}_{\mathcal{O}}^{\bullet}$. The projection π_A is given by $\pi_A(a, b) = a$.

Proof. Consider the map

$$\begin{aligned} \phi: \mathcal{O}[[T]]/(T(T - \lambda^n)) &\rightarrow A \\ f &\mapsto (f(0), f(\lambda^n)). \end{aligned}$$

- **ϕ is welldefined and respects the \mathcal{O} -algebra structure:** Let f_0 be the constant term of a polynomial f and $f_1 := T^{-1}(f - f_0)$, so that $f = f_0 + T \cdot f_1(T)$. Because of

$$f(0) - f(\lambda^n) = (f_0 + 0 \cdot f_1(0)) - (f_0 + \lambda^n \cdot f_1(\lambda^n)) = -\lambda^n \cdot f_1(\lambda^n),$$

$f(0) \equiv f(\lambda^n) \pmod{\lambda^n}$ as required. Furthermore,

$$\phi(T(T - \lambda^n)) = (0(-\lambda^n), \lambda^n(\lambda^n - \lambda^n)) = (0, 0).$$

Also, we need to think about series in $\mathcal{O}[[T]]$ with infinitely many terms. For the first component $f(0)$ this doesn't matter, as ϕ just takes the constant term. As \mathcal{O} is complete with respect to the λ -adic topology, the map $\tilde{\phi}_2: \mathcal{O}[[T]] \rightarrow \mathcal{O}$, $f \mapsto f(\lambda^n)$ is clearly welldefined and thus ϕ is welldefined. Let $o \in \mathcal{O}$. Then

$$\phi(of) = (of(0), of(\lambda^n)) = o(f(0), f(\lambda^n)) = o\phi(f)$$

- **Injectivity:** Let $\phi(f) = 0$. Then $f(0) = 0 \implies T|f$ and $f(\lambda^n) = 0 \implies (T - \lambda)|f$. As a result, $f \in T(T - \lambda^n)$.
- **Surjectivity:** Let $(a, b) \in A$. As $a \equiv b \pmod{\lambda^n}$, we can write $b = a + b' \cdot \lambda^n$. Because of

$$\phi(\overline{a + b'T}) = (a, a + b'\lambda^n) = (a, b),$$

ϕ is surjective.

- $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$: \mathcal{O} is noetherian, so $\mathcal{O}[T]/(T(T - \lambda^n))$ is noetherian as well. (λ, T) is a maximal ideal in $\mathcal{O}[T]/(T(T - \lambda^n))$, because

$$(\mathcal{O}[T]/(T(T - \lambda^n))) / (\lambda, T) = \mathcal{O}/(\lambda) = k.$$

Therefore, the completion $\mathcal{O}[T]/(T(T - \lambda^n))^{\wedge(\lambda, T)}$ of $\mathcal{O}[T]/(T(T - \lambda^n))$ with respect to (λ, T) is a local ring with maximal ideal (λ, T) . Consider the SES of finitely generated \mathcal{O} -modules

$$0 \rightarrow (T(T - \lambda^n))\mathcal{O}[T] \rightarrow \mathcal{O}[T] \rightarrow \mathcal{O}[T]/(T(T - \lambda^n)) \rightarrow 0.$$

As completion of finitely generated \mathcal{O} -modules is exact (because \mathcal{O} is noetherian), we get the SES

$$0 \rightarrow (T(T - \lambda^n))\mathcal{O}[[T]] \rightarrow \mathcal{O}[[T]] \rightarrow \mathcal{O}[T]/(T(T - \lambda^n))^{\wedge(\lambda, T)} \rightarrow 0.$$

by completing with respect to (λ, T) . As a result, we have

$$\mathcal{O}[T]/(T(T - \lambda^n))^{\wedge(\lambda, T)} = \mathcal{O}[[T]]/(T(T - \lambda^n)).$$

Hence, $\mathcal{O}[[T]]/(T(T - \lambda^n))$ is a local ring with maximal ideal (λ, T) . Therefore, its residue field is

$$\mathcal{O}[[T]]/(T(T - \lambda^n))/(\lambda, T) = \mathcal{O}[T]/(T(T - \lambda^n))/(\lambda, T) = \mathcal{O}/(\lambda) = k.$$

As $\mathcal{O}[T]/(T(T - \lambda^n))$ is noetherian, its (λ, T) -completion $\mathcal{O}[[T]]/(T(T - \lambda^n))$ is again noetherian [cf. AM69, theorem 10.26]. In total, we get that $A \cong \mathcal{O}[[T]]/(T(T - \lambda^n))$ is a local, complete, noetherian \mathcal{O} -algebra with residue field $k \implies A \in \mathcal{C}_{\mathcal{O}}$.

- **A is a finite flat complete intersection:** A is generated by $(1, 1)$ and $0, \lambda^n$ because

$$(a, b) = a(1, 1) + (0, \underbrace{b - a}_{\in \lambda^n}) = a(1, 1) + c(0, \lambda^n).$$

Also, A is torsion-free because \mathcal{O} is an integral domain. As there is one variable and one relation in $A \cong \mathcal{O}[[T]]/(T(T - \lambda^n))$, A is a complete intersection. □

Example 2.4. [cf. DDT95, example 5] $U = \mathcal{O}[[X_1, \dots, X_n]]$ with projection $\pi_U: U \rightarrow \mathcal{O}$, $f \mapsto f(0)$ lies in $\mathcal{C}_{\mathcal{O}}^{\bullet}$.

Proof. \mathcal{O} is noetherian, so $\mathcal{O}[X_1, \dots, X_n]$ is noetherian as well. $(\lambda, X_1, \dots, X_n)$ is a maximal ideal in $\mathcal{O}[X_1, \dots, X_n]$, because

$$(\mathcal{O}[X_1, \dots, X_n]) / (\lambda, X_1, \dots, X_n) = \mathcal{O}/(\lambda) = k.$$

Therefore, the completion

$$\mathcal{O}[X_1, \dots, X_n]^{\wedge(\lambda, X_1, \dots, X_n)} = \mathcal{O}[[X_1, \dots, X_n]]$$

of $\mathcal{O}[X_1, \dots, X_n]$ with respect to $(\lambda, X_1, \dots, X_n)$ is a local ring with maximal ideal $(\lambda, \widehat{X_1, \dots, X_n})$. Its residue field is $\mathcal{O}[[X_1, \dots, X_n]]/(\lambda, X_1, \dots, X_n) = k$, as required. As $\mathcal{O}[X_1, \dots, X_n]$ is noetherian, its $(\lambda, X_1, \dots, X_n)$ -completion is again noetherian. □

Remark 2.5. In example 2.3 we could write A as a quotient of $\mathcal{O}[[X]]$. This is possible in a more general setting, in fact every finitely generated $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ can be written as a quotient of $U = \mathcal{O}[[X_1, \dots, X_n]]$ for suitable n .

Proof. As A is a noetherian ring and $\ker \pi_A$ is an ideal in A , it is finitely generated and therefore also finitely generated as an A -module. As A is finitely generated as an \mathcal{O} -module, $\ker \pi_A$ is also finitely generated as an \mathcal{O} -module. Consider the map

$$\begin{aligned}\Phi: U = \mathcal{O}[[X_1, \dots, X_n]] &\rightarrow A \\ X_i &\mapsto a_i,\end{aligned}$$

where $\ker \pi_A = (a_1, \dots, a_n)$ and π_U is given by $f \mapsto f(0)$. That π_U is welldefined follows from the universal property of the ring of formal power series because the target ring \mathcal{O} is complete. As (X_1, \dots, X_n) generate the kernel of π_U , this is a map in $\mathcal{C}_{\mathcal{O}}^{\bullet}$. We have the short exact sequences

$$0 \rightarrow \ker \pi_A \rightarrow A \rightarrow \operatorname{im} \pi_A \cong \mathcal{O} \rightarrow 0$$

and

$$0 \rightarrow \ker \pi_U \rightarrow U \rightarrow \operatorname{im} \pi_U \cong \mathcal{O} \rightarrow 0$$

As both corresponding sequences split via the inclusion $\mathcal{O} \hookrightarrow A, x \mapsto x \cdot 1$ resp. $\mathcal{O} \hookrightarrow U$, we can write $U \cong \mathcal{O} \oplus \ker \pi_U$ and $A \cong \mathcal{O} \oplus \ker \pi_A$. Φ by definition induces an equality on the first component, a surjection on the second and therefore is surjective on the direct sum. \square

Remark 2.6. For a finite flat complete intersection $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ we can choose the quotient

$$U \xrightarrow{\alpha} U/(f_1, \dots, f_n) \cong A$$

in such a way that the augmentation map π_A is induced by

$$\pi_U: \mathcal{O}[[X_1, \dots, X_n]] \rightarrow \mathcal{O}, \quad f(X_1, \dots, X_n) \mapsto f(0, \dots, 0).$$

Because $[f_i] = 0 \in A$, necessarily

$$f_i(0) = \pi_U(f_i) = \pi_A(\Phi(f_i)) = \pi_A(0) = 0,$$

i.e. the relations f_i must not have a constant term.

Proof. From remark 2.5 we know that we can express A as a quotient of U ,

$$A \cong \mathcal{O}[[X_1, \dots, X_n]]/(\ker \Phi).$$

Considering the definition of Φ , the statement on π_A follows. By [Mat86, theorem 21.2] it follows that $\ker \Phi$ can be generated by n elements. Hence we find f_1, \dots, f_n s.t.

$$A \cong \mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n).$$

\square

Note that whenever we write a complete intersection A as a quotient of U , without loss of generality we can choose polynomials without constant term and assume that π_A is induced by evaluation at 0 on U .

Definition 2.7. Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$. Then

$$\phi_A := (\ker \pi_A) / (\ker \pi_A)^2.$$

Example 2.8. Remember the definition of U in example 2.4. The tangent space $\phi_U = \ker \pi_U / (\ker \pi_U)^2$ is

$$\mathcal{O}X_1 \oplus \cdots \oplus \mathcal{O}X_n.$$

Indeed, elements of $f \in \ker \pi_U$ have no constant term as $f(0) = 0$ and therefore are multiples of X . Elements in $\ker \pi_U^2$ are multiples of X^2 . As a result, we receive elements $\bar{f} \in \phi_U$ by cutting off all higher terms of a power series $f \in \ker \pi_U$.

Remark 2.9. Write A as a quotient of U , $A = U / (f_1, \dots, f_m)$. This is possible because of remark 2.5. We then get $\phi_A = \phi_U / (\bar{f}_1, \dots, \bar{f}_m)$. As a quotient of ϕ_U its a finitely generated \mathcal{O} -module.

Proof. Consider the following map of \mathcal{O} -modules

$$\begin{aligned} \Phi: \ker \pi_U &\rightarrow (\ker \pi_A) / (\ker \pi_A)^2 = \phi_A \\ f &\mapsto [f] \mod (\ker \pi_A)^2, \end{aligned}$$

where $[f]$ denotes the image of f in A . Then, as $\pi_A([f]) = f(0)$, we get that $X_i \in \ker \pi_A \forall i$ and therefore $[f] \in \ker \pi_A \forall f \in \ker \pi_U$. Not only is Φ welldefined, we can conclude that $X_i \in \ker \pi_A \implies X_i^2 \in (\ker \pi_A)^2$ and therefore Φ is also surjective and $(\ker \pi_U)^2 \subset \ker \Phi$.

With this knowledge we get a welldefined surjective map

$$\begin{aligned} \tilde{\Phi}: \phi_U = \mathcal{O}X_1 \oplus \cdots \oplus \mathcal{O}X_n &\rightarrow \phi_A \\ a_1X_1 + \cdots + a_nX_n \mod (\ker \pi_U)^2 &\mapsto [a_1X_1 + \cdots + a_nX_n] \mod (\ker \pi_A)^2. \end{aligned}$$

Elements in the kernel of this map are either generated by X_i^2 so they vanish modulo $(\ker \pi_A)^2$ or they become 0 by sending them to $A = U / (f_i)$. As higher order terms of f_i are vanishing anyways, the kernel of $\tilde{\Phi}$ is generated by the \bar{f}_i , i.e.

$$\phi_A \cong \phi_U / (\bar{f}_i)$$

□

Example 2.10. We now compute ϕ_A where A was defined in example 2.3. Remember that $f = T(T - \lambda^n) = -\lambda^n T + T^2$. Therefore,

$$\phi_A = \mathcal{O}T / (-\lambda^n T) = \mathcal{O} / \lambda^n.$$

Definition 2.11. Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$. Then

$$\eta_A := \pi_A(\text{Ann}_A(\ker \pi_A))$$

is an ideal in \mathcal{O} .

Example 2.12. We now compute η_U for U from example 2.4.

$$\begin{aligned}\eta_U &= \pi_U(\text{Ann ker } \pi_U) \\ &= \pi_U(\text{Ann } \mathcal{O}X_1 \oplus \cdots \oplus \mathcal{O}X_n) \\ &= \pi_U(0) = 0.\end{aligned}$$

Lemma 2.13. Let $\mathfrak{a} \subset \mathcal{O}$ be an ideal. Then

$$\mathfrak{a} \neq 0 \implies \mathcal{O}/\mathfrak{a} \text{ finite.}$$

Proof. As \mathcal{O} is a DVR, $\mathfrak{a} = \lambda^n$ for some $n \in \mathbb{N}$ where λ is the maximal ideal in \mathcal{O} . Therefore, $\mathcal{O}/\mathfrak{a} = \mathcal{O}/\lambda^n$.

Using the fact that $\lambda = (t)$ for some uniformizer t , we get $\forall i \geq 1$ the isomorphism $\lambda^i/\lambda^{i+1} \cong \mathcal{O}/\lambda = k$ and thereby also the short exact sequence

$$0 \rightarrow \mathcal{O}/\lambda \cong \lambda^i/\lambda^{i+1} \rightarrow \mathcal{O}/\lambda^{i+1} \rightarrow \mathcal{O}/\lambda^i \rightarrow 0.$$

As $k = \mathcal{O}/\lambda$ is finite, we can use induction

$$\#\mathcal{O}/\lambda^{i+1} = \#\mathcal{O}/\lambda \cdot \#\mathcal{O}/\lambda^i = \#k \cdot (\#k)^i = (\#k)^{i+1}$$

and get $\#\mathcal{O}/\mathfrak{a} = \#\mathcal{O}/\lambda^n = (\#k)^n$. □

Example 2.14. We now compute η_A for A from example 2.3.

$$\begin{aligned}\eta_A &= \pi_A(\text{Ann ker } \pi_A) \\ &= \pi_A(\text{Ann}\{(0, b) \in \mathcal{O} \times \mathcal{O} \mid b \equiv 0 \pmod{\lambda^n}\}) \\ &= \pi_A(\{(a, 0) \in \mathcal{O} \times \mathcal{O} \mid a \equiv 0 \pmod{\lambda^n}\}) \\ &= \pi_A((\lambda^n) \times 0) \\ &= (\lambda^n)\end{aligned}$$

Example 2.15. [cf. DDT95, example 3] $A = \mathcal{O}[[X]]/(X^2)$ with augmentation $\pi_A: A \rightarrow \mathcal{O}$, $f \mapsto f(0)$ is a finite flat complete intersection in $\mathcal{C}_{\mathcal{O}}^{\bullet}$. Furthermore, $\phi_A = \mathcal{O}$ and $\eta_A = 0$.

Proof. $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ is analogous to example 2.3.

$$\phi_A = \phi_U/(\overline{X^2}) = \mathcal{O}X/(0) \cong \mathcal{O}$$

and

$$\pi_A(\text{Ann}_A \text{ker } \pi_A) = \pi_A(\text{Ann}_A X\mathcal{O}[[X]]) = \pi_A(X\mathcal{O}[[X]]) = (0).$$

□

Example 2.16. [DDT95, section 5.1, example 2]

$$A = \{(a, b, c) \in \mathcal{O}^3, a \equiv b \equiv c \pmod{\lambda}\}$$

is finite flat and element of $\mathcal{C}_{\mathcal{O}}^{\bullet}$ with augmentation $\pi_A(a, b, c) := a$. Furthermore,

$$\phi_A \cong \mathcal{O}/\lambda\mathcal{O} \times \mathcal{O}/\lambda\mathcal{O}, \quad \eta_A = (\lambda)$$

Proof. One can show that

$$\mathcal{O}[[X, Y]]/(X(X - \lambda), Y(Y - \lambda), XY) \cong A$$

via $f \mapsto (f(0, \lambda), f(\lambda, 0), f(0, 0))$. Then ϕ_A is easy to compute. η_A is computed analogous to example 2.14. \square

Example 2.17. [DDT95, section 5.1, example 4]

$$A = \{(a, b, c, d) \in \mathcal{O}^4, a \equiv b \equiv c \equiv d \pmod{\lambda}, a + d \equiv b + c \pmod{\lambda^2}\}$$

is finite flat and element of $\mathcal{C}_{\mathcal{O}}^{\bullet}$ with augmentation $\pi_A(a, b, c) := a$. Furthermore,

$$\phi_A \cong \mathcal{O}/\lambda\mathcal{O} \times \mathcal{O}/\lambda\mathcal{O}, \eta_A = (\lambda^2)$$

Proof. One can show that

$$\mathcal{O}[[X, Y]]/(X(X - \lambda), Y(Y - \lambda)) \cong A$$

via $f \mapsto (f(0, 0), f(0, \lambda), f(\lambda, 0), f(\lambda, \lambda))$. Then ϕ_A is easy to compute and

$$\begin{aligned} \eta_A &= \pi_A(\text{Ann}_A \ker \pi_A) = \pi_A(\text{Ann}_A \{(0, b, c, d) \in A\}) \\ &= \pi_A(\{(a, 0, 0, 0) \in \mathcal{O}^4, a \equiv 0 \pmod{\lambda^2}\}) = \lambda^2 \end{aligned}$$

\square

After these examples we now state Wiles' numerical criterion.

Theorem 2.18. [DDT95, theorem 5.3] *Let $R \twoheadrightarrow T$ a surjective morphism in $\mathcal{C}_{\mathcal{O}}^{\bullet}$, T finite flat and $\eta_T \neq 0$ (i.e. \mathcal{O}/η_T finite). Then the following are equivalent.*

- (a) $\#\phi_R \leq \#(\mathcal{O}/\eta_T)$,
- (b) $\#\phi_R = \#(\mathcal{O}/\eta_T)$,
- (c) R and T are complete intersections, and $R \rightarrow T$ is an isomorphism.

2.3 Basic properties of the invariants

In this subsection we prove the equivalence (a) \Leftrightarrow (b) in theorem 2.18 by investigating the invariants ϕ_A and η_A that we defined last section.

Lemma 2.19. *A morphism $f: A \rightarrow B \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ induces a homomorphism $\phi_A \rightarrow \phi_B$ of \mathcal{O} -modules. This induced map is surjective if and only if the morphism $A \rightarrow B$ is surjective.*

For the 'only if'-part, see [DDT95, lemma 5.5; Mat86, theorem 8.4; Har77, ch. II, lemma 7.4; Sta22, section 090T].

Proof. We have the commutative diagram

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ \pi_A \searrow & & \swarrow \pi_B \\ & \mathcal{O} & \end{array}.$$

It follows from the diagram that the restriction of f to $\ker \phi_A$ maps to $\ker \phi_B$, because $\forall x \in \ker \phi_A: \pi_B(f(x)) = \pi_A(x) = 0$. Concatenating this with the projection to the tangent space, we get a map

$$\tilde{f}: \ker \pi_A \rightarrow \ker \pi_B / (\ker \pi_B)^2 = \phi_B.$$

In order to see that $\tilde{f}: \phi_A \rightarrow \phi_B$ is welldefined, we need to show

$$f(\ker \pi_A)^2 \subset (\ker \pi_B)^2.$$

However, this follows from the fact that $f(\ker \pi_A) \subset \ker \pi_B$ and that f is an algebra homomorphism:

$$f(x^2) = \underbrace{f(x)}_{\in \ker \pi_B} \underbrace{f(x)}_{\in \ker \pi_B} \in (\ker \pi_B)^2$$

for any $x \in \ker \pi_A$.

First, let us assume that $A \rightarrow B$ is a surjective map. In this case, every element $x \in \ker \phi_B$ has a preimage in $\ker \pi_A$. Indeed, $\forall y \in f^{-1}(x) \subset A$:

$$\pi_A(y) = \pi_B(f(y)) = \pi_B(x) = 0.$$

As a result, the induced map $f: \ker \pi_A \rightarrow \ker \pi_B$ and its concatenation with the projection to ϕ_B , $\tilde{f}: \ker \pi_A \rightarrow \ker \pi_B / (\ker \pi_B)^2$ are both surjective. In total, we obtain a surjective homomorphism $\tilde{f}: \phi_A \rightarrow \phi_B$.

Now, let the induced map $\phi_A \rightarrow \phi_B$ be surjective. Consider the ideal $I = f(\ker \pi_A) \cdot B$ in B . Let $x \in I$. Then $x = \sum_i f(x_i) \cdot b_i$ for $x_i \in \ker \pi_A$ and $b_i \in B$. Remember the commutative diagram from the beginning of the proof,

$$\pi_B(x) = \pi_B \left(\sum_i f(x_i) \cdot b_i \right) = \sum_i \pi_B(f(x_i)) \cdot \pi_B(b_i) = \sum_i \pi_A(x_i) \cdot \pi_B(b_i) = 0.$$

As a result, $I \subset \ker \pi_B \subset \mathfrak{m}_B$. Note that

$$f(\ker \pi_A) \subset f(\ker \pi_A) \cdot B \implies f((\ker \pi_A)^n) = f(\ker \pi_A)^n \subset (f(\ker \pi_A) \cdot B)^n,$$

so we have $f((\ker \pi_A)^n) \cdot B \subset I^n$. As B is \mathfrak{m}_B -adically complete and therefore Hausdorff, we get

$$\bigcap_{n \in \mathbb{N}} f((\ker \pi_A)^n) \cdot B \subset \bigcap_{n \in \mathbb{N}} I^n \subset \bigcap_{n \in \mathbb{N}} \mathfrak{m}_B^n = 0,$$

i.e. B is separated with respect to the I -adic topology. Furthermore, $\ker \pi_A$ is finitely generated as an A -module, $\ker \pi_A = \langle a_1, \dots, a_m \rangle$ because A is noetherian. As $\ker \pi_A \rightarrow (\ker \pi_B)/(\ker \pi_B)^2$ is surjective, we have

$$(\ker \pi_B)/(\ker \pi_B)^2 = \langle \overline{f(a_1)}, \dots, \overline{f(a_m)} \rangle_B.$$

As A is \mathfrak{m}_A -adically complete, $\ker \pi_A$ is finitely generated over A and $\ker \pi_A \subset \mathfrak{m}_A$, A is $\ker \pi_A$ -adically complete as well [cf. Sta22, lemma 10.96.8]. Furthermore, I is separated with respect to the I -adic topology as a submodule of B . Together with the fact that A is $\ker \pi_A$ -adically complete, we can apply Nakayama's Lemma as in Mat, 8.4. It follows that the images $\langle f(a_1), \dots, f(a_m) \rangle$ generate $\ker \pi_B$ as a B -module. We already know that $f(\ker \pi_A) \cdot B \subset \ker \pi_B$. In total we have

$$f(\ker \pi_A) \cdot B = \ker \pi_B.$$

Now we conclude that 1 is a generator of $B/I = B/f(\ker \pi_A)B = B/\ker \pi_B = \mathcal{O}$ as an $A/\ker \pi_A \cong \mathcal{O}$ -module. Applying Nakayama's Lemma again, we get that 1 is a generator of B as an A -module and hence, $f: A \rightarrow B$ is surjective. \square

Corollary 2.20. *Let $A, B \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ and ϕ_A be finite. If $A \rightarrow B$ is surjective, then*

$$\#\phi_A \geq \#\phi_B.$$

Lemma 2.21. *If $f: A \rightarrow B$ is surjective, then*

$$\eta_A \subset \eta_B, \quad \text{i.e. if } \eta_A \neq 0, \quad \#(\mathcal{O}/\eta_A) \geq \#(\mathcal{O}/\eta_B).$$

Proof. As we have seen in the proof of lemma 2.19, a surjective map f induces a surjective map on the kernels, $f: \ker \pi_A \rightarrow \ker \pi_B$. Now let $x \in \text{Ann}_A \ker \pi_A$, i.e. $x \cdot a = 0 \quad \forall a \in \ker \pi_A$. For all $b \in \ker \pi_B$ and any preimage $a \in \ker \pi_A$ we have

$$f(x) \cdot b = f(x) \cdot f(a) = f(x \cdot a) = f(0) = 0.$$

As a result, $f(x) \in \text{Ann}_B \ker \pi_B$ and we obtain a map

$$\tilde{f}: \text{Ann}_A \ker \pi_A \rightarrow \text{Ann}_B \ker \pi_B.$$

In order to show $\eta_A \subset \eta_B$, let $x \in \eta_A = \pi_A(\text{Ann}_A \ker \pi_A)$, i.e. $x = \pi_A(y)$ for some $y \in \text{Ann}_A \ker \pi_A$. By the commutative diagram

$$\begin{array}{ccc} \text{Ann}_A \ker \pi_A & \xrightarrow{\tilde{f}} & \text{Ann}_B \ker \pi_B \\ & \searrow \pi_A & \swarrow \pi_B \\ & \mathcal{O} & \end{array},$$

we get

$$x = \pi_A(y) = \pi_B(\tilde{f}(y)) \in \pi_B(\text{Ann}_B \ker \pi_B) \implies x \in \eta_B,$$

as desired. \square

Definition 2.22. Let M be a finitely generated R -module. Then M is a quotient

$$P: R^n \longrightarrow M = R^n / \ker P$$

We define $\text{Fitt}_R(M) := \langle \det(v_1, \dots, v_n) | v_i \in \ker P \rangle_R \subset R$. This is independent of the choice of the surjection (see e.g. [Sta22, section 07Z6]).

Lemma 2.23. For a finitely generated R -module M we have

$$\text{Fitt}_R(M) \subset \text{Ann}_R(M).$$

Proof. M is generated by the residue classes of the canonical basis of R^n ,

$$M = \langle \bar{e}_1, \dots, \bar{e}_n \rangle_R$$

where \bar{x} may denote the residue class of $x \bmod \ker P$. Now let $[v_1 | \dots | v_n]$ be a matrix with $v_i \in \ker P$. Then this matrix annihilates M because it annihilates all the generators \bar{e}_i ,

$$[v_1 | \dots | v_n] \cdot e_i = v_i \in \ker P.$$

Let A be the adjugate matrix of $[v_1 | \dots | v_n]$, i.e.

$$A[v_1 | \dots | v_n] = \det[v_1 | \dots | v_n] \cdot I_{n \times n}.$$

Let $m \in M$ and $(m_i)_{i=1}^n$ a lift in R^n . Then we have

$$\begin{aligned} \det[v_1 | \dots | v_n] \cdot m &= \det[v_1 | \dots | v_n] \cdot I_{n \times n} (m_i)_{i=1}^n \\ &= A[v_1 | \dots | v_n] \left(\sum_{i=1}^n m_i e_i \right) \\ &= A \cdot \sum_{i=1}^n m_i v_i \in A \cdot \ker P \subset \ker P \end{aligned}$$

Therefore $\text{Fitt}_R(M) \subset \text{Ann}_R(M)$. □

Remark 2.24 (Fitting ideals and \otimes). Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ and M a finitely generated A -module. Note that \mathcal{O} has an A -module structure via π_A . We have

$$\pi_A(\text{Fitt}_A(M)) = \text{Fitt}_{\mathcal{O}}(M \otimes_A \mathcal{O}).$$

This follows from the fact that $- \otimes_A \mathcal{O}$ is right exact. Hence, from the exact sequence

$$\ker P \longrightarrow A^n \longrightarrow M \longrightarrow 0$$

we get the exact sequence

$$\ker P \otimes_A \mathcal{O} \longrightarrow A^n \otimes_A \mathcal{O} = \mathcal{O}^n \longrightarrow M \otimes_A \mathcal{O} \longrightarrow 0.$$

The remaining details are left as an exercise to the reader.

Remark 2.25 (Fitting ideals for finitely generated \mathcal{O} -modules). Let M be a finitely generated \mathcal{O} -module. As \mathcal{O} is a PID, there are unique $r, s \in \mathbb{N}$ and $n_1 \geq \dots \geq n_s \in \mathbb{N}$ s.t.

$$M = \mathcal{O}^r \oplus \mathcal{O}/\lambda^{n_1} \oplus \dots \oplus \mathcal{O}/\lambda^{n_s}.$$

If $r > 0$, then every $v \in \ker P \subset \mathcal{O}^{r+s}$ has r zero components. Therefore, $\text{Fitt}_R(M) = 0$ for $r > 0$. If $r = 0$, the i -th component of $v \in \ker P \subset \mathcal{O}^s$ lies in the kernel of $\mathcal{O} \rightarrow \mathcal{O}/\lambda^{n_i}$, i.e. $v_i \in \lambda^{n_i}$. Using the Leibniz formula for computing the determinant, we get $\text{Fitt}_{\mathcal{O}}(M) = \lambda^{n_1} \dots \lambda^{n_s} = \lambda^{n_1 + \dots + n_s}$.

Corollary 2.26. *Let M be a finite \mathcal{O} -module. Then*

$$\#M = \#(\mathcal{O}/\text{Fitt}_{\mathcal{O}}(M)).$$

Proof. As M is finite, we get

$$M = \mathcal{O}/\lambda^{n_1} \oplus \dots \oplus \mathcal{O}/\lambda^{n_s}$$

and

$$\text{Fitt}_{\mathcal{O}}(M) = \lambda^{n_1 + \dots + n_s}.$$

From the proof of lemma 2.13 it follows that

$$\#M = (\#k)^{n_1} \dots (\#k)^{n_s} = (\#k)^{n_1 + \dots + n_s}$$

and

$$\#(\mathcal{O}/\text{Fitt}_{\mathcal{O}}(M)) = \#(\mathcal{O}/\lambda^{n_1 + \dots + n_s}) = (\#k)^{n_1 + \dots + n_s}.$$

□

Lemma 2.27. *Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ s.t. ϕ_A finite and $\eta_A \neq 0$. Then*

$$\#\phi_A \geq \#(\mathcal{O}/\eta_A).$$

Proof. As $\mathcal{O} = A/\ker \pi_A$, we have

$$\ker \pi_A \otimes_A \mathcal{O} = \ker \pi_A \otimes_A A/\ker \pi_A \cong \ker \pi_A/(\ker \pi_A)^2 = \phi_A.$$

We therefore have

$$\text{Fitt}_{\mathcal{O}}(\phi_A) = \text{Fitt}_{\mathcal{O}}(\ker \pi_A \otimes_A \mathcal{O}) = \pi_A(\text{Fitt}_A(\ker \pi_A))$$

where the second equality follows from remark 2.24. Applying lemma 2.23, we get

$$\text{Fitt}_{\mathcal{O}}(\phi_A) \subset \pi_A(\text{Ann}_A(\ker \pi_A)) = \eta_A.$$

As ϕ_A is finite, we can apply corollary 2.26 to $M = \phi_A$ and obtain

$$\#\phi_A = \#(\mathcal{O}/\text{Fitt}_{\mathcal{O}}(\phi_A)) \geq \#(\mathcal{O}/\eta_A).$$

□

Proposition 2.28. [cf. DDT95, corollary 5.6] $(a) \Leftrightarrow (b)$ in theorem 2.18.

Proof. By assumption, $R \rightarrow T$ is a surjective morphism in $\mathcal{C}_{\mathcal{O}}^{\bullet}$. With corollary 2.20 it follows that $\#\phi_R \geq \#\phi_T$. Lemma 2.27 tells us that $\#\phi_T \geq \#(\mathcal{O}/\eta_T)$. The inequalities combine to

$$\#\phi_R \geq \#(\mathcal{O}/\eta_T).$$

In both cases the finiteness of \mathcal{O}/η_T implies the finiteness of ϕ_R and from that we obtain the finiteness of $\#\phi_T$. (a) gives us $\#\phi_R \leq \#(\mathcal{O}/\eta_T)$, so combined with $\#\phi_R \geq \#(\mathcal{O}/\eta_T)$ we conclude that (b) must hold. (b) \Rightarrow (a) is clear. \square

2.4 Regular sequences and the Koszul complex

Let A be a finite flat complete intersection. Hence we can write

$$A = \mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n).$$

The goal of this section is to prove some technical lemmata and to introduce the Koszul complex that we will use to construct two $\mathcal{O}[[X]]$ -free resolutions for A . This will turn out to be crucial in the next section.

We start with a few definitions from commutative algebra, closely following [DDT95, section 5.3]

Definition 2.29 (primary ideal). Let R be a local ring and $\mathfrak{a} \subsetneq R$ an ideal. \mathfrak{a} is said to be primary if every zero divisor in R/\mathfrak{a} is nilpotent.

Recall that the dimension of a ring is given by

$$\sup \{n | \mathfrak{p}_0 \subsetneq \dots \subsetneq \mathfrak{p}_n \subsetneq R, \mathfrak{p}_i \text{ prime}\}.$$

Definition 2.30 (system of parameters). Let x_1, \dots, x_n generate a primary ideal of R . If $n = \dim R$ then x_1, \dots, x_n is called a system of parameters.

Lemma 2.31. [DDT95, lemma 5.10] *The sequence $(f_1, \dots, f_n, \lambda)$ is a system of parameters for U (cf. example 2.4).*

Proof. First, we show that $\dim U = n + 1$. We have an ascending chain of prime ideals

$$(0) \subsetneq (\lambda) \subsetneq \dots \subsetneq (\lambda, X_1, \dots, X_n),$$

so by definition of the dimension we get

$$\dim U \geq n + 1. \tag{1}$$

Let $\mathfrak{m} = (\lambda, X_1, \dots, X_n)$. We have seen that this is the maximal ideal in U . Now we can conclude

$$\dim U \leq \dim_{U/\mathfrak{m}}(\mathfrak{m}/\mathfrak{m}^2) = \dim_k(\lambda/\lambda^2 \oplus kX_1 \oplus \dots \oplus kX_n).$$

As $\lambda/\lambda^2 \cong k$ (cf. lemma 2.13), the above expression evaluates to $n + 1$ and we have

$$\dim U \leq n + 1. \quad (2)$$

Taking the inequalities 1 and 2 together, we obtain $\dim U = n + 1$. It remains to show that $(f_1, \dots, f_n, \lambda)$ generate a primary ideal of U . U is local and therefore the quotient ring

$$\tilde{U} := U/(f_1, \dots, f_n, \lambda)$$

is local as well. Also, \tilde{U} is a k -vector space (because it's an \mathcal{O} -module and λ -operation annihilates it). As $A = U/(f_1, \dots, f_n)$ is a finitely generated \mathcal{O} -module, we can find (x_1, \dots, x_N) that generate A as \mathcal{O} -module. These x_i then generate \tilde{U} as a k -vector space. As k is finite, the whole vector space is finite. As a result, the chain of powers of $\mathfrak{m}_{\tilde{U}}$ must stabilize,

$$\mathfrak{m}_{\tilde{U}}^n = \mathfrak{m}_{\tilde{U}}^{n+1}$$

By Nakayama's lemma it follows that $\mathfrak{m}_{\tilde{U}}^n = 0$. Hence, every element of the maximal ideal is nilpotent. As zero-divisors are never units, they are contained in the maximal ideal and, a fortiori, nilpotent. In total, f_1, \dots, f_n, λ generate a primary ideal of U . \square

Definition 2.32 (regular sequence). [cf. Mat86, §16] A sequence (x_1, \dots, x_n) is said to be a regular sequence if $\forall i = 1, \dots, n$:

$$x_i \text{ is not a zero-divisor in } R/(x_1, \dots, x_{i-1}).$$

Definition 2.33 (depth). The depth of a local noetherian ring R is defined as the maximum length of a regular sequences in R . (in \mathfrak{m} ?)

Theorem 2.34. *All maximal regular sequences have the same length.*

Definition 2.35 (Cohen-Macaulay). A local ring R is called Cohen-Macaulay if

$$\text{depth } R = \dim R.$$

Lemma 2.36. [DDT95, lemma 5.11] *The sequence (f_1, \dots, f_n) is a regular sequence for U .*

Proof. The sequence $(\lambda, X_1, \dots, X_n)$ is a regular sequence for U because $U/\lambda = k[[X_1, \dots, X_n]]$ and $U/(\lambda, X_1, \dots, X_{i-1}) = k[[X_i, \dots, X_n]]$ are integral domains (hence obviously X_i can't be a zero-divisor in these rings). As we have seen in the previous lemma, it's as well a system of parameters. Therefore, the depth of U (i.e. the maximal length of any regular sequence in U) is bigger than the length of the particular regular sequence $(\lambda, X_1, \dots, X_n)$. In total we get $\text{depth } U \geq \dim U$, because $(\lambda, X_1, \dots, X_n)$ is a system of parameters as well. In general, we have $\text{depth } R \leq \dim R$ for a noetherian local ring R , so combined we have

$$\text{depth } U = \dim U$$

and hence, U is Cohen-Macaulay. As $(f_1, \dots, f_n, \lambda)$ is a system of parameters and U is Cohen-Macaulay it follows that $(f_1, \dots, f_n, \lambda)$ is a regular sequence [Mat86, theorem 17.4]. A fortiori, the sequence (f_1, \dots, f_n) is also a regular sequence. \square

Corollary 2.37. [DDT95, corollary 5.12] *Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ be finitely generated and of the form*

$$A \cong \mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n).$$

Then A is flat.

Proof. Assume that A is not flat, i.e. there is a $\lambda^m u \in \mathcal{O}$ and a

$$0 \neq g(X_1, \dots, X_n) \in A \quad \text{s.t.} \quad \lambda^m u \cdot g(\underline{X}) = 0.$$

Consider $g' = \lambda^{m-1}ug$. If g' is still zero, define $g'' := \lambda^{m-2}ug$. After finitely many steps we find a $0 \neq g \in A$ s.t. $\lambda g = 0$, i.e.

$$\lambda \cdot g(\underline{X}) = c_1(\underline{X})f_1(\underline{X}) + \dots + c_n(\underline{X})f_n(\underline{X}).$$

Without loss of generality we can choose the $c_i(\underline{X})$ in such a way that $c_i(\underline{X})$ is never divisible by any of the $f_j(\underline{X})$ for $j < i$. (In such a case one would have to add a suitable multiple of f_i to c_j .) Furthermore, $\exists i: 0 \neq c_i \pmod{\lambda}$. Otherwise we could divide the whole equation by λ and obtain $g = 0 \pmod{(f_1, \dots, f_n)}$, a contradiction. Let i_0 be the biggest such i . In the proof of lemma 2.31 we have never used that A is flat, only that it is finitely generated. Therefore we know that λ, f_1, \dots, f_n is a system of parameters for U . From the proof of lemma 2.36 (where we also haven't used that A is flat) we can deduce that λ, f_1, \dots, f_n is also a regular sequence for U and, a fortiori, f_{i_0} is not a zero-divisor in $U/(\lambda, f_1, \dots, f_{i_0-1})$. If we consider the equation

$$\lambda \cdot g(\underline{X}) = c_1(\underline{X})f_1(\underline{X}) + \dots + c_n(\underline{X})f_n(\underline{X}).$$

$\text{mod } (\lambda, f_1, \dots, f_{i_0-1})$ we obtain

$$0 = 0 + c_{i_0}f_{i_0} + 0,$$

as all other terms are in the ideal $(\lambda, f_1, \dots, f_{i_0-1})$. We know that c_{i_0} is not divisible by any of $\lambda, f_1, \dots, f_{i_0}$. Therefore f_{i_0} is a zero-divisor in $U/(\lambda, f_1, \dots, f_{i_0-1})$. This is a contradiction, so our assumption must be false. \square

Definition 2.38 (Koszul complex). [DDT95, ch. 5.3; Mat86, §16] The Koszul complex associated to a sequence $\underline{x} = (x_1, \dots, x_n)$ contained in the maximal ideal of a local ring is given by the complex

$$0 \rightarrow K_n(\underline{x}, R) \xrightarrow{d_n} K_{n-1}(\underline{x}, R) \rightarrow \dots \rightarrow K_0(\underline{x}, R) \rightarrow 0,$$

where

$$K_p(\underline{x}, R) := \bigoplus_{i_1 < \dots < i_p} R \cdot u_{i_1} \wedge \dots \wedge u_{i_p}$$

for symbols u_1, \dots, u_n . The differential map $d_p: K_p(\underline{x}, R) \rightarrow K_{p-1}(\underline{x}, R)$ is given by

$$d_p(u_{i_1} \wedge \dots \wedge u_{i_p}) = \sum_{t=1}^p (-1)^t x_{i_t} \cdot u_{i_1} \wedge \dots \wedge \widehat{u_{i_t}} \wedge \dots \wedge u_{i_p}.$$

We denote the p -th homology group of this complex as $H_p(\underline{x}, R)$.

Remark 2.39. [DDT95, proposition 5.13; Mat86, theorem 16.5 (i)] We note that $K_0(\underline{x}, R) = R$ and therefore compute

$$H_0(\underline{x}, R) = K_0(\underline{x}, R) / (\text{im } d_1) \cong R / (x_1, \dots, x_n) = R / (\underline{x}).$$

Furthermore, one can show that if (\underline{x}) is a regular sequence, then the complex is exact. As it consists of free R -modules, homological algebra shows that we then get a resolution of $H_0(\underline{x}, R) = R / (\underline{x})$ by free R -modules.

2.5 Complete intersections and Gorenstein rings

Let A be a finite flat complete intersection in $\mathcal{C}_{\mathcal{O}}^{\bullet}$. The goal of this section is to show that A satisfies a Gorenstein condition, i.e. a specific form of self-duality. This fact can then be used to show (c) \implies (b) in theorem 2.18. Although there is a very general notion of Gorenstein rings, for the purpose of this proof we only need a special case,

Definition 2.40. Let $A \in \mathcal{C}_{\mathcal{O}}$ be finite flat. A is called Gorenstein, if there is an isomorphism of A -modules

$$\Psi: \text{Hom}_{\mathcal{O}}(A, \mathcal{O}) \cong A.$$

Our goal therefore reduces to constructing an A -module isomorphism

$$\text{Hom}_{\mathcal{O}}(A, \mathcal{O}) \rightarrow A.$$

We start with some useful constructions and conventions.

Notation. For any ring R write $R[[\underline{X}]] := R[[X_1, \dots, X_n]]$.

Let a_1, \dots, a_n be the images in A of X_1, \dots, X_n by the natural map

$$\alpha: \mathcal{O}[[\underline{X}]] \rightarrow A = \mathcal{O}[[\underline{X}]] / (f_1, \dots, f_n),$$

and let

$$\beta: A[[\underline{X}]] \rightarrow A$$

be the map which sends X_i to a_i . A polynomial $f \in A[[\underline{X}]]$ is sent to 0 exactly when $f(a_1, \dots, a_n) = 0$. Therefore, $\exists i: (X_i - a_i) | f$ and hence, the sequence $g_i = (X_i - a_i)$ generates the kernel of β . View the f_i as polynomials in $A[[\underline{X}]]$ via the inclusion $\mathcal{O} \hookrightarrow A$. Then $\forall i = 1, \dots, n$:

$$\beta(f_i) = f_i(a_1, \dots, a_n) = 0 \in \mathcal{O}[[\underline{X}]] / (f_1, \dots, f_n).$$

Therefore every of the f_i is element of $\ker \beta$ and hence can be written as an $A[[X]]$ -linear combination of the g_i ,

$$(f_1, \dots, f_n) = (g_1, \dots, g_n)M,$$

where M is an $n \times n$ matrix with coefficients in $A[[X]]$. Let $D = \det(M) \in A[[X]]$. The projection $\mathcal{O}[[X]] \rightarrow A$ induces an $\mathcal{O}[[X]]$ -module structure on A .

Lemma 2.41. [see DDT95, lemma 5.14] *The map*

$$\begin{aligned} \Phi: \operatorname{Hom}_{\mathcal{O}[[X]]}(A[[X]], \mathcal{O}[[X]]) &\rightarrow A \\ f &\mapsto \alpha(f(D)) \end{aligned}$$

is an $\mathcal{O}[[X]]$ -linear surjection.

Proof. As shown in lemma 2.36, $(\underline{f}) = (f_1, \dots, f_n)$ is a regular sequence for $\mathcal{O}[[X]]$. In the ring $A[[X]]/(X_1 - a_1, \dots, X_{i-1} - a_{i-1})$, there are no relations in X_i , i.e. it can be written as $R[X_i]$ for a ring R . Therefore $(X_i - a_i)$ can't be a zero-divisor. As this holds for all $i = 1, \dots, n$, $(\underline{g}) = (g_i) = (X_i - a_i)$ is a regular sequence for $A[[X]]$.

Let now $K(\underline{f}, \mathcal{O}[[X]])$ and $K(\underline{g}, A[[X]])$ be the associated Koszul complexes. We have that $\bar{K}(\underline{f}, \mathcal{O}[[X]])$ is a resolution of

$$A = H_0(\underline{f}, \mathcal{O}[[X]]) = \mathcal{O}[[X]]/(\underline{f}_1, \dots, \underline{f}_n)$$

by free $\mathcal{O}[[X]]$ -modules and analogous that $K(\underline{g}, A[[X]])$ is a resolution of

$$A = H_0(\underline{g}, A[[X]]) = A[[X]]/(X_1 - a_1, \dots, X_n - a_n)$$

by free $A[[X]]$ -modules. Every free $A[[X]]$ -module has a canonical $\mathcal{O}[[X]]$ -module structure (take the canonical inclusion $\mathcal{O} \hookrightarrow A, x \mapsto x \cdot 1$ and extend it to a map $\mathcal{O}[[X]] \hookrightarrow A[[X]]$).

In the following, we want to construct a map of complexes

$$\Phi: K(\underline{f}, \mathcal{O}[[X]]) \rightarrow K(\underline{g}, A[[X]]).$$

On level 0, we define

$$\phi_0: K_0(\underline{f}, \mathcal{O}[[X]]) = \mathcal{O}[[X]] \rightarrow K_0(\underline{g}, A[[X]]) = A[[X]]$$

to be just the canonical inclusion $\mathcal{O}[[X]] \hookrightarrow A[[X]]$ as explained above. On the first level, let

$$\Phi_1: K_1(\underline{f}, \mathcal{O}[[X]]) = \bigoplus_{i=1}^n R \cdot u_i \rightarrow K_1(\underline{g}, A[[X]]) = \bigoplus_{i=1}^n R \cdot v_i$$

be the map defined by

$$(\Phi_1(u_1), \dots, \Phi_1(u_n)) = (v_1, \dots, v_n)M.$$

By skew-linearity this can be extended to a map of exterior algebras. In the following we proof that Φ

1. is a morphism of complexes,
2. induces the identity on $A = H_0(\underline{f}, \mathcal{O}[[\underline{X}]])$
3. and satisfies

$$\Phi_n(u_1 \wedge \cdots \wedge u_n) = D \cdot v_1 \wedge \cdots \wedge v_n.$$

1. **Φ is a morphism of complexes.** It is clear by definition that Φ is welldefined on every level. We have to show that Φ commutes with the differentials of the complex,

$$\begin{aligned} \Phi_{p-1}(d(u_{i_1} \wedge \cdots \wedge u_{i_p})) &= \Phi_{p-1} \left(\sum_{t=1}^p (-1)^t x_{i_t} u_{i_1} \wedge \cdots \wedge \widehat{u_{i_t}} \wedge \cdots \wedge u_{i_p} \right) \\ &= \sum_{t=1}^p (-1)^t x_{i_t} \Phi_1(u_{i_1}) \wedge \cdots \wedge \widehat{\Phi_1(u_{i_t})} \wedge \cdots \wedge \Phi_1(u_{i_p}) \\ &= d(\Phi_1(u_{i_1}) \wedge \cdots \wedge \Phi_1(u_{i_p})) \\ &= d(\Phi_p(u_{i_1} \wedge \cdots \wedge u_{i_p})). \end{aligned}$$

2. **Φ induces the identity on $A = H_0(\underline{f}, \mathcal{O}[[\underline{X}]])$**

We have the following commutative diagram

$$\begin{array}{ccccccc} \bigoplus_{i=1}^n u_i \mathcal{O}[[\underline{X}]] &= K_1(\underline{f}, \mathcal{O}[[\underline{X}]]) & \xrightarrow{d_1} & K_0(\underline{f}, \mathcal{O}[[\underline{X}]]) &= \mathcal{O}[[\underline{X}]] & \xrightarrow{d_0} & 0 \\ \downarrow \Phi_1 & & & & \downarrow \Phi_0 & & \\ \bigoplus_{i=1}^n v_i A[[\underline{X}]] &= K_1(\underline{g}, A[[\underline{X}]]) & \xrightarrow{d_1} & K_0(\underline{g}, A[[\underline{X}]]) &= A[[\underline{X}]] & \xrightarrow{d_0} & 0 \end{array}.$$

As

$$H_0(\underline{f}, \mathcal{O}[[\underline{X}]]) = \frac{\ker d_0}{\operatorname{im} d_1} = \frac{\mathcal{O}[[\underline{X}]]}{(f_1, \dots, f_n)}$$

and

$$H_0(\underline{g}, A[[\underline{X}]]) = \frac{\ker d_0}{\operatorname{im} d_1} = \frac{A[[\underline{X}]]}{(g_1, \dots, g_n)}$$

we can take a look at the map

$$\mathcal{O}[[\underline{X}]] \rightarrow \frac{A[[\underline{X}]]}{(X_1 - a_1, \dots, X_n - a_n)} = A.$$

This map sends X_i to $a_i \in A$. By definition of $A = \mathcal{O}[[\underline{X}]]/(f_1, \dots, f_n)$ and a_i as image of X_i under α this is exactly the map α . Hence, the induced map

$$A = \mathcal{O}[[\underline{X}]]/(f_1, \dots, f_n) \rightarrow \frac{A[[\underline{X}]]}{(X_1 - a_1, \dots, X_n - a_n)} = A$$

is identity.

3. Let $M = (M_{i,j})_{i,j}$. Then we have

$$\begin{aligned}
\Phi_n(u_1 \wedge \cdots \wedge u_n) &= \Phi(u_1) \wedge \cdots \wedge \Phi(u_n) \\
&= \sum_{j=1}^n v_j M_{j,1} \wedge \cdots \wedge \sum_{j=1}^n v_j M_{j,n} \\
&= \sum_{\sigma \in \mathfrak{S}(n)} \underbrace{(-1)^{\text{sgn}(\sigma)} \prod_{i=1}^n M_{i,\sigma(i)}}_{=\det M} \cdot v_1 \wedge \cdots \wedge v_n \\
&= D \cdot v_1 \wedge \cdots \wedge v_n,
\end{aligned}$$

where $\mathfrak{S}(n)$ may denote the group of permutations.

In the following we write $K_\bullet(f) = K_\bullet(f, \mathcal{O}[[X]])$ and $K_\bullet(g) = K_\bullet(g, A[[X]])$. By applying the functor $\text{Hom}_{\mathcal{O}[[X]]}(-, \mathcal{O}[[X]])$ to the two free resolutions, we get the following commutative diagram

$$\begin{array}{ccccc}
\begin{array}{c} \xrightarrow{d_{n-1}^*} \text{Hom}_{\mathcal{O}[[X]]}(K_{n-1}(f), \mathcal{O}[[X]]) \xrightarrow{d_n^*} \text{Hom}_{\mathcal{O}[[X]]}(K_n(f), \mathcal{O}[[X]]) \longrightarrow 0 \\ \Phi_{n-1}^* \uparrow \qquad \qquad \qquad \Phi_n^* \uparrow \end{array} & & \\
\begin{array}{c} \xrightarrow{d_{n-1}^*} \text{Hom}_{\mathcal{O}[[X]]}(K_{n-1}(g), \mathcal{O}[[X]]) \xrightarrow{d_n^*} \text{Hom}_{\mathcal{O}[[X]]}(K_n(g), \mathcal{O}[[X]]) \longrightarrow 0 \end{array} & &
\end{array}$$

As both resolutions are free and, a fortiori, projective we can use the fact from homological algebra that there exists a homotopy equivalence that induces identity on the zero-th homology groups. Consider the following commutative diagram with exact rows

$$\begin{array}{ccccccc}
\bigoplus_{i=1}^n u_i \mathcal{O}[[X]] & \xrightarrow{d_1} & \mathcal{O}[[X]] & \xrightarrow{\alpha} & A & \longrightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow \text{id} & & \\
\bigoplus_{i=1}^n v_i A[[X]] & \xrightarrow{d_1} & A[[X]] & \xrightarrow{X_i \mapsto a_i} & A & \longrightarrow & 0
\end{array}$$

From projectiveness we can conclude that there is a lift of the map $\text{id} \circ \alpha$ to a map $\mathcal{O}[[X]] \rightarrow A[[X]]$ along the map $X_i \mapsto a_i$. As both maps send $X_i \mapsto a_i$, our lift is given by $X_i \mapsto X_i$, i.e. it is exactly Φ_0 . By commutativity, $(f_1, \dots, f_n) = \text{im } d_1 = \ker \alpha$ maps to the kernel of $X_i \mapsto a_i$. Therefore, we can lift the map $\Phi_0 \circ d_1$ along the surjective map

$$d_1: \bigoplus_{i=1}^n v_i A[[X]] \rightarrow \text{im } d_1 = \ker(X_i \mapsto a_i) = (g_1, \dots, g_n).$$

Using $(f_1, \dots, f_n) = (g_1, \dots, g_n)M$, we obtain for the induced map f

$$\begin{aligned}
d_1(f(u_i)) &= \Phi_0(d_1(u_i)) = \Phi_0(-f_i) \\
&= - \sum_{j=1}^n g_j m_{ji} = \sum_{j=1}^n d_1(v_j) m_{ji} = d_1 \left(\sum_{j=1}^n v_j m_{ji} \right).
\end{aligned}$$

We note that $f = \Phi_1$. As the higher maps are then uniquely defined by skew linearity, Φ extends to a homotopy equivalence. As $\text{Hom}_{\mathcal{O}[[\underline{X}]]}(-, \mathcal{O}[[\underline{X}]])$ is an additive functor, Φ^* is also a homotopy equivalence. Hence, we have an isomorphism on the n -th cohomology,

$$\Phi_n^*: \text{Hom}_{\mathcal{O}[[\underline{X}]]}(K_n(\underline{g}), \mathcal{O}[[\underline{X}]]) / (\text{im } d_n^*) \rightarrow \text{Hom}_{\mathcal{O}[[\underline{X}]]}(K_n(\underline{f}), \mathcal{O}[[\underline{X}]]) / (\text{im } d_n^*).$$

We know that

$$\begin{aligned} K_n(\underline{f}) &= \bigoplus_{i=1}^n \mathcal{O}[[\underline{X}]] \cdot u_1 \wedge \cdots \wedge u_n \cong \mathcal{O}[[\underline{X}]] \quad \text{and} \\ K_n(\underline{g}) &= \bigoplus_{i=1}^n A[[\underline{X}]] \cdot u_1 \wedge \cdots \wedge u_n \cong A[[\underline{X}]]. \end{aligned}$$

Therefore, we can make the identification

$$\text{Hom}_{\mathcal{O}[[\underline{X}]]}(K_n(\underline{f}), \mathcal{O}[[\underline{X}]]) \cong \text{Hom}_{\mathcal{O}[[\underline{X}]]}(\mathcal{O}[[\underline{X}]], \mathcal{O}[[\underline{X}]]) \cong \mathcal{O}[[\underline{X}]],$$

where the second isomorphism sends $f \mapsto f(1)$. The lift of 1 under the first isomorphism is $u_1 \wedge \cdots \wedge u_n$. Hence in total we send a map f to $f(u_1 \wedge \cdots \wedge u_n)$. As a next step, we compute the image of d_n^* in $\mathcal{O}[[\underline{X}]]$. Let $\varphi \in \text{Hom}_{\mathcal{O}[[\underline{X}]]}(K_{n-1}(\underline{f}), \mathcal{O}[[\underline{X}]])$. Then we have

$$d_n^*(\varphi) = \varphi \circ d_n: K_n(\underline{f}) \xrightarrow{d_n} K_{n-1}(\underline{g}) \xrightarrow{\varphi} \mathcal{O}[[\underline{X}]],$$

where the composition is given by

$$\varphi(d_n(u_1 \wedge \cdots \wedge u_n)) = \sum_{t=1}^n (-1)^t f_t \varphi(v_1 \wedge \cdots \wedge \widehat{v}_t \wedge \cdots \wedge v_n),$$

as φ is $\mathcal{O}[[\underline{X}]]$ -linear. By our identification we then send the whole map to

$$\varphi \circ d_n(u_1 \wedge \cdots \wedge u_n) = \sum_{t=1}^n (-1)^t f_t \varphi(v_1 \wedge \cdots \wedge \widehat{v}_t \wedge \cdots \wedge v_n) \in \mathcal{O}[[\underline{X}]].$$

The image of d_n^* is therefore generated by the f_t and we get

$$\text{Hom}_{\mathcal{O}[[\underline{X}]]}(K_n(\underline{f}), \mathcal{O}[[\underline{X}]]) / (\text{im } d_n^*) \cong \mathcal{O}[[\underline{X}]] / (f_1, \dots, f_n) = A.$$

As a result, Φ_n^* induces a $\mathcal{O}[[\underline{X}]]$ -linear surjection

$$\Phi: \text{Hom}_{\mathcal{O}[[\underline{X}]]}(A[[\underline{X}]], \mathcal{O}[[\underline{X}]]) \cong \text{Hom}_{\mathcal{O}[[\underline{X}]]}(K_n(\underline{g}), \mathcal{O}[[\underline{X}]]) \twoheadrightarrow A.$$

Φ takes a $\mathcal{O}[[\underline{X}]]$ -linear map and applies Φ_n^* to f , resulting in

$$f \circ \Phi_n: \mathcal{O}[[\underline{X}]] \xrightarrow{\Phi_n} K_n(\underline{g}) \xrightarrow{f} \mathcal{O}[[\underline{X}]].$$

After that it uses our previous identification $\text{Hom}_{\mathcal{O}[[X]]}(\mathcal{O}[[X]], \mathcal{O}[[X]]) \cong \mathcal{O}[[X]]$ and sends $f \circ \Phi_n$ to its value on 1. Using the identifications $K_n(f) \cong \mathcal{O}[[X]]$ and $K_n(g) \cong A[[X]]$, we obtain

$$f \circ \Phi_n(1) = f \circ \Phi_n(u_1 \wedge \cdots \wedge u_n) = f(D \cdot v_1 \wedge \cdots \wedge v_n) = f(D).$$

Finally we have to take the residue class mod (f_1, \dots, f_n) . That is done by applying the projection map α . In total we get

$$\Phi(f) = \alpha(f(D)),$$

as desired. \square

Lemma 2.42. [DDT95, lemma 5.15] *Let*

$$\tilde{\cdot}: \text{Hom}_{\mathcal{O}}(A, \mathcal{O}) \rightarrow \text{Hom}_{\mathcal{O}[[X]]}(A[[X]], \mathcal{O}[[X]])$$

be the map that assigns an $\mathcal{O}[[X]]$ -homomorphism $\tilde{f}: A[[X]] \rightarrow \mathcal{O}[[X]]$ to the \mathcal{O} -homomorphism $f: A \rightarrow \mathcal{O}$ by extending it with $X \mapsto X$. Then define

$$\Psi: \text{Hom}_{\mathcal{O}}(A, \mathcal{O}) \rightarrow A$$

via $\Psi(f) = \alpha(\tilde{f}(D))$. This is an A -module isomorphism where the A -module structure on $\text{Hom}_{\mathcal{O}}(A, \mathcal{O})$ is given by $a \cdot f = (x \mapsto f(ax))$. In particular, A is Gorenstein.

Proof. 1. Ψ is A -linear. This is the key point of this proof. For any $a \in A, a' \in \mathcal{O}[[X]]$ we have by definition of Ψ

$$\Psi(af) = \alpha(\tilde{f}(aD)) = \alpha(\tilde{f}((a-a')D + a'D)) = \alpha(\tilde{f}((a-a')D)) + \alpha(\tilde{f}(a'D)),$$

where in the last step we have used the linearity of \tilde{f} and α . Now choose $a' \in \alpha^{-1}(a) \subset \mathcal{O}[[X]]$, as α is surjective. We can also understand a' as an element of $A[[X]]$ via the inclusion $\iota: \mathcal{O}[[X]] \hookrightarrow A[[X]]$. It follows $\beta(\iota(a')) = \alpha(a') = a = \beta(a)$. Therefore, $a - \iota(a') \in \ker \beta$. By definition of the g_i as generators of $\ker \beta$, we can write $a - \iota(a')$ as an $A[[X]]$ -linear combination of the g_i . We further have

$$(f_1, \dots, f_n) = (g_1, \dots, g_n) \cdot M.$$

Multiplying with the adjugate matrix M' we get

$$(f_1, \dots, f_n) \cdot M' = (g_1, \dots, g_n) \cdot \underbrace{M \cdot M'}_{=D \cdot I_{n \times n}}.$$

Hence, we can write $g_i \cdot D$ (and therefore also $(a - \iota(a')) \cdot D$) as an $A[[X]]$ -linear combination of the f_i ,

$$(a - \iota(a')) \cdot D = \sum_{i=1}^n a_i f_i.$$

Using the $\mathcal{O}[[\underline{X}]]$ -linearity of \tilde{f} , we compute

$$\begin{aligned}\alpha(\tilde{f}((a - a')D)) &= \alpha\left(\tilde{f}\left(\sum_{i=1}^n a_i f_i\right)\right) \\ &= \alpha\left(\sum_{i=1}^n f_i \tilde{f}(a_i)\right) = \sum_{i=1}^n \alpha(f_i \cdot \tilde{f}(a_i)) = 0,\end{aligned}$$

as $f_i \in \ker \alpha$. Putting our results together, we obtain

$$\Psi(af) = \alpha(\tilde{f}((a - a')D)) + \alpha(\tilde{f}(a'D)) = \alpha(\tilde{f}(a'D)),$$

and again by $\mathcal{O}[[\underline{X}]]$ -linearity of \tilde{f} we conclude

$$\Psi(af) = \alpha(a' \tilde{f}(D)) = a\alpha(\tilde{f}(D)) = a\Psi(f).$$

2. Ψ is surjective. As A is a finite flat \mathcal{O} -algebra, we know by the classification of finitely generated modules over principal ideal domains that A consists of a free part and a torsion part. Because it is flat, however, the torsion part is 0 and therefore A is a free \mathcal{O} -module. Therefore we have \mathcal{O} -module-isomorphisms

$$\mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O}) \cong \mathrm{Hom}_{\mathcal{O}}(\mathcal{O}^r, \mathcal{O}) \cong \mathcal{O}^r,$$

where r may denote the rank of \mathcal{O} . Therefore A and $\mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O})$ are both free A -modules of the same finite rank r . Now let us consider base change from \mathcal{O} to $\mathcal{O}[[\underline{X}]]$. We have [cf. Sta22, lemma 10.14.3]

$$\mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O}[[\underline{X}]]) \cong \mathrm{Hom}_{\mathcal{O}[[\underline{X}]]}(A[[\underline{X}]], \mathcal{O}[[\underline{X}]])$$

as $\mathcal{O}[[\underline{X}]]$ -modules. Because of

$$\mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O}[[\underline{X}]]) \cong \mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O}) \otimes_{\mathcal{O}} \mathcal{O}[[\underline{X}]]$$

[Bou89, chapter I, §2, section 9], an \mathcal{O} -basis f_1, \dots, f_r of $\mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O})$ is an $\mathcal{O}[[\underline{X}]]$ -basis of $\mathrm{Hom}_{\mathcal{O}}(A, \mathcal{O}[[\underline{X}]])$. By base change, the extended maps $\tilde{f}_1, \dots, \tilde{f}_r$ form an $\mathcal{O}[[\underline{X}]]$ -basis of $\mathrm{Hom}_{\mathcal{O}[[\underline{X}]]}(A[[\underline{X}]], \mathcal{O}[[\underline{X}]])$. From lemma 2.41 we know that the map

$$\Phi: \mathrm{Hom}_{\mathcal{O}[[\underline{X}]]}(A[[\underline{X}]], \mathcal{O}[[\underline{X}]]) \rightarrow A$$

is surjective. Therefore, $\forall a \in A: \exists p_1, \dots, p_r \in \mathcal{O}[[\underline{X}]]$ s.t.

$$a = \Phi(p_1 \tilde{f}_1 + \dots + p_r \tilde{f}_r).$$

Now we can use the linearity of the involved maps,

$$a = \alpha((p_1 \tilde{f}_1 + \dots + p_r \tilde{f}_r)(D)) = \Psi(\alpha(p_1) f_1 + \dots + \alpha(p_r) f_r).$$

3. Ψ is injective. Analogous to the theorem for vector spaces, we know that a surjective homomorphism between two free modules of the same finite rank is also injective. (Note that the reverse implication doesn't hold, injective homomorphisms between free modules of the same finite rank are not necessarily surjective.) As this condition is satisfied by $\text{Hom}_{\mathcal{O}}(A, \mathcal{O})$ and A , the lemma follows. \square

2.6 Explicit computation of η for complete intersections

In this section, A is always a finite flat complete intersection $\in \mathcal{C}_{\mathcal{O}}^{\bullet}$, i.e. $A \cong \mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n)$. The goal of this section is to find explicit formulas for η_A and ϕ_A using the relations f_i . This allows us to show that (c) \implies (b) in theorem 2.18. We closely follow [DDT95, chapter 5.4].

Notation. $A^{\vee} := \text{Hom}_{\mathcal{O}}(A, \mathcal{O})$ and similarly, $\pi_A^{\vee}: \mathcal{O}^{\vee} \rightarrow A^{\vee}$ may denote the dual map associated to $\pi_A: A \rightarrow \mathcal{O}$.

As we have seen in the last section, $A^{\vee} \cong A$ as A is a complete intersection. We choose one A -module isomorphism $\Psi: A^{\vee} \rightarrow A$.

Lemma 2.43. *Any two A -module isomorphisms $\Psi, \Psi': A^{\vee} \rightarrow A$ differ by a unit in A .*

Proof. The composition $\Psi' \circ \Psi^{-1}: A \rightarrow A$ is an A -module isomorphism from A to A . Such an isomorphism is uniquely defined by its value on 1,

$$\Psi' \circ \Psi^{-1}(x) = x \cdot \Psi' \circ \Psi^{-1}(1).$$

As we have the same fact for the inverse map, we find that $\Psi' \circ \Psi^{-1}(1) \in A^{\times}$. $\Psi \circ \Psi^{-1}(1) = 1$, so $\Psi' \circ \Psi^{-1} = x \cdot \Psi \circ \Psi^{-1}$. We conclude $\Psi = x \cdot \Psi'$. \square

Lemma 2.44. *Regardless of the choice of Ψ , we have $\Psi\pi_A^{\vee}(\mathcal{O}^{\vee}) = \text{Ann}_A \ker \pi_A$ and, a fortiori*

$$\eta_A = \pi_A \Psi \pi_A^{\vee}(\mathcal{O}^{\vee}).$$

Proof. We first show $\Psi\pi_A^{\vee}(\mathcal{O}^{\vee}) \subset \text{Ann}_A \ker \pi_A$. Let therefore $\phi: \mathcal{O} \rightarrow \mathcal{O} \in \mathcal{O}^{\vee}$ and $x \in \ker \pi_A$. It suffices to show that $\Psi\pi_A^{\vee}(\phi) \cdot x = 0$. Taking into account the A -module structure of $\text{Hom}_{\mathcal{O}}(A, \mathcal{O})$ and the fact that Ψ is an A -module-isomorphism, we obtain

$$\Psi\pi_A^{\vee}(\phi) \cdot x = \Psi(\phi \circ \pi_A) \cdot x = \Psi(x \cdot \phi \circ \pi_A) = \Psi((y \mapsto \phi \circ \pi_A(x \cdot y))) = 0,$$

as $x \in \ker \pi_A$. In order to prove $\Psi\pi_A^{\vee}(\mathcal{O}^{\vee}) \supset \text{Ann}_A \ker \pi_A$, let $a \in \text{Ann}_A \ker \pi_A$ and $f \in \text{Hom}_{\mathcal{O}}(A, \mathcal{O})$ s.t. $\Psi(f) = a$. Then $\forall x \in \ker \pi_A$,

$$0 = \Psi(f) \cdot x = \Psi((y \mapsto f(x \cdot y))) \implies f(x \cdot y) = 0 \quad \forall y \in A \implies f(x) = 0.$$

A fortiori, $\ker \pi_A \subset \ker f$ and we get an induced map $\tilde{f}: \mathcal{O} \cong A/\ker \pi_A \rightarrow \mathcal{O}$ s.t. $f = \tilde{f} \circ \pi_A$. As a result, we can write

$$a = \Psi(f) = \Psi(\tilde{f} \circ \pi_A) = \Psi(\pi_A^{\vee}(\tilde{f})) \in \Psi(\pi_A^{\vee}(\mathcal{O}^{\vee})).$$

\square

Lemma 2.45. *Let*

$$\tilde{\cdot}: \text{Hom}_{\mathcal{O}}(A, \mathcal{O}) \rightarrow \text{Hom}_{\mathcal{O}[[X]]}(A[[X]], \mathcal{O}[[X]])$$

and Ψ be the maps known from lemma 2.42 and $D = \det M$ as defined in the previous section. Then,

$$\pi_A \Psi \pi_A^\vee(\mathcal{O}^\vee) = \langle \pi_A \alpha \tilde{\pi}_A(D) \rangle_{\mathcal{O}}.$$

Proof. Let $\phi \in \mathcal{O}^\vee = \text{Hom}_{\mathcal{O}}(\mathcal{O}, \mathcal{O})$. Then $\phi(x) = x \cdot \phi(1) \in \mathcal{O}$. Therefore

$$\Psi(\pi_A^\vee(\phi)) = \Psi(\phi \circ \pi_A) = \alpha(\tilde{\phi} \circ \tilde{\pi}_A(D)) = \alpha(\phi(1) \cdot \tilde{\pi}_A(D)).$$

Using the \mathcal{O} -linearity of α and π_A , we get

$$\pi_A(\Psi(\pi_A^\vee(\phi))) = \phi(1) \cdot \pi_A \alpha \tilde{\pi}_A(D) \in \langle \pi_A \alpha \tilde{\pi}_A(D) \rangle_{\mathcal{O}}.$$

For the other inclusion, let $x \cdot \pi_A \alpha \tilde{\pi}_A(D) \in \langle \pi_A \alpha \tilde{\pi}_A(D) \rangle_{\mathcal{O}}$ with $x \in \mathcal{O}$. Then define $\phi(y) = y \cdot x \in \mathcal{O}^\vee$. By the calculations we have done so far it becomes clear that this is the required preimage. \square

Proposition 2.46. [DDT95, proposition 5.19]

$$\eta_A = (\det(\partial f_i / \partial X_j(0))).$$

Proof. We have

$$\eta_A = \pi_A \Psi \pi_A^\vee(\mathcal{O}^\vee) = \langle \pi_A \alpha \tilde{\pi}_A(D) \rangle_{\mathcal{O}}.$$

Consider the equation

$$(f_1, \dots, f_n) = (X_1 - [X_1], \dots, X_n - [X_n]) \cdot (m_{i,j})_{i,j}.$$

Applying $\tilde{\pi}_A$ to the whole equation leaves the f_i unchanged because $\tilde{\pi}_A(X_i) = X_i$ and the coefficients of the f_i are elements of \mathcal{O} that are not affected by π_A because of its \mathcal{O} -linearity. In the following we make use of remark 2.6. On the RHS, we get $\tilde{\pi}_A(X_i - [X_i]) = X_i - \pi_A([X_i]) = X_i$, as π_A is the evaluation at 0 for preimages of A in $\mathcal{O}[[X_1, \dots, X_n]]$. Denote the image of $m_{i,j}$ under $\tilde{\pi}_A$ with $\tilde{m}_{i,j} \in \mathcal{O}[[X_1, \dots, X_n]]$. Now compute

$$\frac{\partial f_i}{\partial X_j}(0) = \frac{\partial \sum_{k=1}^n X_k \tilde{m}_{k,i}}{\partial X_j}(0) = \tilde{m}_{j,i}(0) + \sum_{k=1}^n X_k \frac{\partial \tilde{m}_{k,i}}{\partial X_j} \Big|_0 = \tilde{m}_{j,i}(0).$$

The composition $\pi_A \circ \alpha$ is given by the evaluation at 0. Because computing the determinant is a linear operation, we get

$$\pi_A \alpha \tilde{\pi}_A(D) = \det(\pi_A \alpha \tilde{m}_{i,j})_{i,j} = \det(\tilde{m}_{i,j}(0))_{i,j} = \det \frac{\partial f_i}{\partial X_j}(0).$$

\square

Corollary 2.47. [DDT95, corollary 5.20] Remembering that we assumed A to be a finite flat complete intersection $\in \mathcal{C}_{\mathcal{O}}^{\bullet}$, we obtain

$$\#\Phi_A = \#(\mathcal{O}/\eta_A),$$

i.e. (c) \implies (b) in theorem 2.18.

Proof. From remark 2.9 we know that

$$\Phi_A \cong \Phi_U/(\overline{f_1}, \dots, \overline{f_n}),$$

where \overline{f} denotes the degree one term of a polynomial. More explicitly, we get

$$\Phi_A \cong \mathcal{O}X_1 \oplus \dots \oplus \mathcal{O}X_n / (a_{f_1,1}X_1 + \dots + a_{f_1,n}X_n, \dots, a_{f_n,1}X_1 + \dots + a_{f_n,n}X_n).$$

Applying the isomorphism $\Phi_U = \mathcal{O}^n$ we obtain

$$\Phi_A \cong \mathcal{O}^n / (v_1, \dots, v_n),$$

where $v_i := (a_{f_i,1}, \dots, a_{f_i,n})$. If we interpret $V = [v_i]_i$ as a matrix and hence an \mathcal{O}^n -endomorphism, then $\text{im } V = (v_1, \dots, v_n)$. Clearly

$$a_{f_i,j} = \frac{\partial f_i}{\partial X_j}(0)$$

and hence

$$V = \left(\frac{\partial f_i}{\partial X_j}(0) \right)_{i,j}.$$

As \mathcal{O} is a PID, we know that there exist invertible \mathcal{O} -matrices S, T s.t.

$$V = SDT$$

for some diagonal matrix

$$D = \begin{pmatrix} d_1 & & \\ & \ddots & \\ & & d_n \end{pmatrix}$$

(Smith normal form). As the endomorphisms enduced by S and T are isomorphisms, we compute

$$\mathcal{O}^n / (SDT)\mathcal{O}^n = \mathcal{O}^n / D\mathcal{O}^n = \mathcal{O}/d_1\mathcal{O} \oplus \dots \oplus \mathcal{O}/d_n\mathcal{O}$$

For Dedekind rings we know that $A/\mathfrak{a}A \cong \mathfrak{b}/\mathfrak{a}\mathfrak{b}$ if $0 \neq \mathfrak{a}, \mathfrak{b}$ are ideals of A . We conclude

$$\#\mathcal{O}/\mathfrak{a}\mathfrak{b} \cong \#\mathcal{O}/\mathfrak{b} \cdot \#\mathfrak{b}/\mathfrak{a}\mathfrak{b} \cong \#\mathcal{O}/\mathfrak{b} \cdot \#\mathcal{O}/\mathfrak{a}$$

and obtain

$$\#\mathcal{O}^n / D\mathcal{O}^n = \#\mathcal{O}/d_1\mathcal{O} \cdot \dots \cdot \#\mathcal{O}/d_n\mathcal{O} = \#\mathcal{O}/d_1 \cdot \dots \cdot d_n\mathcal{O} = \#\mathcal{O}/\det D\mathcal{O}$$

As the ideal generated by units is the whole ring, this is the same as $\#\mathcal{O}/\det V\mathcal{O}$. However, we compute

$$\det V\mathcal{O} = \det\left(\frac{\partial f_i}{\partial X_j}(0)\right)\mathcal{O} = \eta_A.$$

We conclude

$$\#\Phi_A = \#\mathcal{O}^n/V\mathcal{O}^n\#\mathcal{O}/\det V\mathcal{O} = \#\mathcal{O}/\eta_A.$$

□

2.7 Isomorphism theorems

Proposition 2.48. [DDT95, theorem 5.21] *Let $f: A \rightarrow B$ be a $\mathcal{C}_{\mathcal{O}}^{\bullet}$ -morphism and B a finite flat complete intersection. If the tangent spaces ϕ_A, ϕ_B are finite and the induced morphism $\tilde{f}: \phi_A \rightarrow \phi_B$ is an isomorphism, then f is an isomorphism.*

Proof. Consider the following commutative diagram

$$\begin{array}{ccccc} & & A & \xleftarrow{\quad} \ker \pi_A & \longrightarrow \phi_A \\ & \nearrow \nu_A & \downarrow f & \searrow \pi_A & \downarrow \tilde{f} \\ U & & & & \mathcal{O} \\ & \searrow \nu_B & \downarrow & \nearrow \pi_B & \downarrow \\ & & B & \xleftarrow{\quad} \ker \pi_B & \longrightarrow \phi_B \end{array}$$

The projection ν_B arises from the fact that we can write every object in $\mathcal{C}_{\mathcal{O}}^{\bullet}$ as a quotient of U (remark 2.5). As B is a complete intersection, we find n generators $f_i \in U$ s.t. $\ker \nu_B = (f_1, \dots, f_n)$. Note that we need to choose the f_i in such a way that they have no constant term (cf. remark 2.6) Define $b_i := \nu_B(X_i) \in \ker \pi_B$ and choose preimages $a_i \in A$ s.t. $f(a_i) = b_i$. As the triangle involving A, B and \mathcal{O} commutes, we conclude that $\pi_A(a_i) = \pi_B(b_i) = 0$, i.e. $a_i \in \ker \pi_A$.

As X_1, \dots, X_n generate ϕ_U and ν_B is surjective, it is easy to see that b_1, \dots, b_n generate ϕ_B . We know that \tilde{f} is an isomorphism, so a_1, \dots, a_n generate ϕ_A . Define

$$\nu_A: \mathcal{O}[[X_1, \dots, X_n]] \rightarrow A$$

via $\nu_A(X_i) = a_i$. As all generators lie in the image of ν_A , this induces a surjection on ϕ_A . By lemma 2.19 it follows that ϕ is surjective.

Finally, we want to show that $\ker \nu_A = \ker \nu_B$. Let $x \in \ker \nu_A$, i.e. $0 = f(0) = f(\nu_A(x)) = \nu_B(x)$, i.e. $x \in \ker \nu_B$. Therefore it remains to prove the inclusion $\ker \nu_B \subset \ker \nu_A$.

The kernel of

$$\overline{\nu_A}: \phi_U \rightarrow \phi_A$$

is a submodule of the finitely generated \mathcal{O} -module of rank n ϕ_U . As \mathcal{O} is a PID, we know that any submodule is finitely generated of rank $n' \leq n$. Independent

of n' , we can choose n possibly linear dependent generators $\overline{g_1}, \dots, \overline{g_n}$ of the above kernel and then extend these generators to $g_1, \dots, g_n \in \ker \nu_A$. A fortiori, the g_i do not have constant terms.

As the kernel of ν_B is generated by f_1, \dots, f_n and $\ker \nu_A \subset \ker \nu_B$, we find a U -linear combination that can be written in the form

$$(g_1, \dots, g_n) = (f_1, \dots, f_n) \cdot M,$$

where M is a $n \times n$ matrix with entries in U . The g_i and the f_i both have no constant terms. Hence, forgetting all monomials of degree bigger than one (equivalently considering the residue classes $\text{mod } \ker \pi_A^2$ resp. $\ker \pi_B^2$, denoted by $\overline{\cdot}$) forces us to take the constant terms \overline{M} of M ,

$$(\overline{g_1}, \dots, \overline{g_n}) = (\overline{f_1}, \dots, \overline{f_n}) \overline{M}.$$

As the tangent spaces are isomorphic, both $(\overline{g_1}, \dots, \overline{g_n})$ and $(\overline{f_1}, \dots, \overline{f_n})$ generate the same \mathcal{O} -submodule of ϕ_U . Indeed, $\overline{f_1}, \dots, \overline{f_n} = \ker(\ker \pi_U / \ker \pi_U^2 \rightarrow \ker \pi_B / \ker \pi_B^2)$. As a result, we can express each of the $\overline{f_1}, \dots, \overline{f_n}$ as a \mathcal{O} -linear combination of $(\overline{g_1}, \dots, \overline{g_n})$. This gives us an inverse to \overline{M} and we deduce that $\det \overline{M}$ is invertible in \mathcal{O} . A power series is invertible if its constant term is invertible so as a result $\det M$ is invertible as well and we conclude that

$$f_1, \dots, f_n \in \langle g_1, \dots, g_n \rangle_U = \ker \nu_B$$

and, a fortiori,

$$\ker \nu_A = \langle f_1, \dots, f_n \rangle_U \subset \ker \nu_B.$$

In total we obtain $\ker \nu_A = \ker \nu_B$ and we can define the map

$$\nu_A \nu_B^{-1}: B \rightarrow A.$$

This is indeed welldefined: For a given $x \in B$ choose $y, y' \in U$ s.t. $\nu_B(y) = \nu_B(y') = x$. It follows $y' - y \in \ker \nu_B$. Then $\nu_A(y') = \nu_A(y' - y) + \nu_A(y) = 0 + \nu_A(y)$ because $\ker \nu_A = \ker \nu_B$. From the commutativity of the above diagram we get that this is indeed an inverse for f and hence, f is an isomorphism. \square

Remark 2.49. [DDT95, remark 5.22, remark 5.23] Let $A = \mathcal{O}[[X, Y]]/(X(X - \lambda), Y(Y - \lambda))$ be the ring from example 2.17 and $B = \mathcal{O}[[X, Y]]/(X(X - \lambda), Y(Y - \lambda), XY)$ be the ring from example 2.16 and $f: A \rightarrow B$ the canonical projection. Then f induces an isomorphism on the tangent spaces, but is not an isomorphism. The assumption that B is a complete intersection is necessary. However, let $A = A[[X]]/(X^3)$, $B = A[[X]]/(X^2)$ and $f: A \rightarrow B$ the canonical projection. Then $\phi_A \cong \mathcal{O} \cong \phi_B$ (cf. example 2.15), even though f is not an isomorphism: the tangent spaces aren't finite.

Lemma 2.50. *Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ be finite flat. Then the canonical map*

$$A \rightarrow A^{\vee\vee}$$

is injective. As a corollary we have

$$A \neq 0 \implies A^{\vee} \neq 0.$$

Proof. As \mathcal{O} is local, every finitely generated torsion-free \mathcal{O} -module is free and, a fortiori projective. For projective modules we have the existence of a dual basis, i.e. a set of functions

$$\{f_i : i \in I, f_i \in A^\vee = \text{Hom}_{\mathcal{O}}(A, \mathcal{O})\}$$

together with a set of elements

$$\{a_i : i \in I, a_i \in A\}$$

satisfying the properties

1. $\forall a \in A: \quad \#\{i \in I : f_i(a) \neq 0\} < \infty$ and
2. $\forall a \in A: \quad a = \sum_{i \in I} f_i(a) \cdot a_i.$

Now let $0 = (\phi \mapsto \phi(a))$, i.e. $\phi(a) = 0 \forall \phi \in A^\vee$. Then, a fortiori, $f_i(a) = 0 \forall i \in I$. We conclude

$$a = \sum_{i \in I} f_i(a) \cdot a_i = 0$$

and hence, $A \rightarrow A^{\vee\vee}$ is injective. If $A^\vee = 0$ then obviously any homomorphism from A^\vee is 0, a fortiori, $A^{\vee\vee} = 0$. By the injectivity of $A \rightarrow A^{\vee\vee}$ this yields $A = 0$ and we have proved the second part of the lemma. \square

Lemma 2.51. *Let $A \in \mathcal{C}_{\mathcal{O}}^\bullet$ be finite flat. Then*

$$\ker \pi_A \cap \text{Ann}_A \ker \pi_A = 0.$$

Proof. Let $0 \neq x \in \eta_A$ and $x' \in \text{Ann}_A \ker \pi_A$ s.t. $\pi_A(x') = x$. Interpret $x \cdot 1$ as an element of the \mathcal{O} -module A . Then,

$$\pi_A(x \cdot 1 - x') = x \cdot \pi_A(1) - \pi_A(x') = x - x = 0 \implies x \cdot 1 - x' \in \ker \pi_A$$

Take $a \in \ker \pi_A \cap \text{Ann}_A \ker \pi_A$. Then $ax' = 0$, because $a \in \ker \pi_A$ and $x' \in \text{Ann}_A \ker \pi_A$. Together we obtain

$$0 = a \cdot (x \cdot 1 - x') = x \cdot a,$$

i.e. a is \mathcal{O} -torsion. However, A is flat and, a fortiori, torsion-free. Hence, a is 0. \square

Proposition 2.52. *[DDT95, theorem 5.24] Let $f : A \rightarrow B$ be a $\mathcal{C}_{\mathcal{O}}^\bullet$ -morphism, A and B finite flat and A a complete intersection. If $\eta_A = \eta_B \neq 0$, then f is an isomorphism.*

Proof. By lemma 2.42, A is Gorenstein, i.e.

$$A^\vee = \text{Hom}_{\mathcal{O}}(A, \mathcal{O}) \cong A \quad \text{as } A\text{-modules,}$$

where the A -module structure is given via $a \cdot \phi = (x \mapsto \phi(a \cdot x))$. By lemma 2.51 $\ker \pi_A \cap \text{Ann}_A \ker \pi_A = 0$ and likewise for B . The fundamental theorem of homomorphisms gives us an isomorphism

$$\text{Ann}_A \ker \pi_A = \text{Ann}_A \ker \pi_A / (\ker \pi_A \cap \text{Ann}_A \ker \pi_A) \xrightarrow[\sim]{\pi_A} \eta_A$$

respectively

$$\text{Ann}_B \ker \pi_B = \text{Ann}_B \ker \pi_B / (\ker \pi_B \cap \text{Ann}_B \ker \pi_B) \xrightarrow[\sim]{\pi_B} \eta_B.$$

In total we obtain

$$\text{Ann}_A \ker \pi_A \cong \eta_A \xrightarrow{f} \eta_B \cong \text{Ann}_B \ker \pi_B.$$

As f is a $\mathcal{C}_{\mathcal{O}}^{\bullet}$ -map, we have the commutativity $\pi_A = \pi_B f$. Hence, for all $x \in \ker f$ we compute $\pi_A(x) = \pi_B(f(x)) = \pi_B(0) = 0$, i.e. $x \in \ker \pi_A$. We thereby have shown that $\ker f \subset \ker \pi_A$ and with lemma 2.51 we conclude

$$\ker f \cap \text{Ann}_A \ker \pi_A \subset \ker \pi_A \cap \text{Ann}_A \ker \pi_A = 0.$$

A fortiori, we get an exact sequence of A -modules

$$0 \longrightarrow \ker f \oplus \text{Ann}_A \ker \pi_A \longrightarrow A \longrightarrow A / \ker f \oplus \text{Ann}_A \ker \pi_A \longrightarrow 0. \quad (*)$$

We have

$$A / \ker f \oplus \text{Ann}_A \ker \pi_A \xrightarrow[\sim]{f} B / f(\text{Ann}_A \ker \pi_A) \cong B / \text{Ann}_B \ker \pi_B$$

and via $[b] \mapsto (x \mapsto b \cdot x)$ we get a canonical injection

$$B / \text{Ann}_B \ker \pi_B \hookrightarrow \text{End}_{\mathcal{O}}(\ker \pi_B)$$

As B and therefore $\ker \pi_B$ are torsion-free, we show that $\text{End}_{\mathcal{O}}(\ker \pi_B)$ is torsion-free as well. For, let $0 \neq \phi \in \text{End}_{\mathcal{O}}(\ker \pi_B)$ and $x \in \mathcal{O}$ s.t. $0 = x \cdot \phi = (y \mapsto x \cdot \phi(y))$. As $\phi \neq 0$, there is at least one $\tilde{y} \in \ker \pi_B$ s.t. $\phi(\tilde{y}) \neq 0$. As $\ker \pi_B$ is torsion-free and $x \cdot \phi(\tilde{y}) = 0$ it follows that $x = 0$, i.e. $\text{End}_{\mathcal{O}}(\ker \pi_B)$ is torsion-free. As \mathcal{O} is a Dedekind ring, torsion-freeness implies flatness. Over any local ring, finitely generated flat modules are free and a fortiori projective. Hence, the short exact sequence $(*)$ splits. Functors preserve split exact sequences and therefore applying the contravariant functor $\text{Hom}_{\mathcal{O}}(-, \mathcal{O})$ yields

$$0 \longrightarrow (A / \ker f \oplus \text{Ann}_A \ker \pi_A)^{\vee} \longrightarrow A^{\vee} \longrightarrow (\ker f \oplus \text{Ann}_A \ker \pi_A)^{\vee} \longrightarrow 0.$$

The direct sum of modules is a colimit, so it commutes with the $\text{Hom}_{\mathcal{O}}(-, \mathcal{O})$ -functor and becomes a limit, in this case a product. However, a finite product is isomorphic to the finite coproduct in the category of \mathcal{O} -modules and together with the fact that A is Gorenstein, we obtain

$$A \longrightarrow (\ker f)^{\vee} \oplus (\text{Ann}_A \ker \pi_A)^{\vee} \longrightarrow 0.$$

The functor $- \otimes_A k$ (where we interpret k as an A -module via the canonical projection $A \xrightarrow{\pi_A} \mathcal{O} \twoheadrightarrow \mathcal{O}/\lambda = k$) is right exact (because it's left adjoint to the corresponding Hom-functor). Taking the dimension of the resulting exact sequence gives us

$$1 = \dim_k(A \otimes_A k) \geq \dim_k((\ker f)^\vee \otimes_A k) + \dim_k((\text{Ann}_A \ker \pi_A)^\vee \otimes_A k), \quad (**)$$

because taking the dimension commutes with direct sums. It is clear that

$$\eta_A = \pi_A \text{Ann}_A \ker \pi_A \neq 0 \implies \text{Ann}_A \ker \pi_A \neq 0.$$

By lemma 2.50, $(\text{Ann}_A \ker \pi_A)^\vee \neq 0$. Now let's assume $(\text{Ann}_A \ker \pi_A)^\vee \otimes_A k = 0$, i.e.

$$0 = (\text{Ann}_A \ker \pi_A)^\vee \otimes_A A/\lambda = (\text{Ann}_A \ker \pi_A)^\vee / \lambda(\text{Ann}_A \ker \pi_A)^\vee,$$

which is equivalent to $(\text{Ann}_A \ker \pi_A)^\vee = \lambda(\text{Ann}_A \ker \pi_A)^\vee$ and by Nakayama's lemma for the local ring \mathcal{O} we could conclude that $(\text{Ann}_A \ker \pi_A)^\vee = 0$, contradiction. Therefore $\dim_k(\text{Ann}_A \ker \pi_A)^\vee > 0$ and by $(**)$ we have $(\ker f)^\vee \otimes_A k = 0$. Again,

$$0 = (\ker f)^\vee \otimes_A A/\lambda = (\ker f)^\vee / \lambda(\ker f)^\vee \xrightarrow{\text{Nakayama}} (\ker f)^\vee = 0.$$

Taking the dual and applying lemma 2.50 finally yields $\ker f = 0$. \square

2.8 A resolution lemma

Lemma 2.53. *[DDT95, theorem 5.26] Let $A \in \mathcal{C}_{\mathcal{O}}^\bullet$ be finite flat. Then there is a $\mathcal{C}_{\mathcal{O}}^\bullet$ -morphism $f: \tilde{A} \rightarrow A$ where \tilde{A} is a finite flat complete intersection and f induces an isomorphism on the tangent spaces, $\tilde{f}: \phi_{\tilde{A}} \xrightarrow{\sim} \phi_A$.*

Proof. First, we notice that $\ker \pi_A$ is a finitely generated \mathcal{O} -module. This follows from the fact that submodules of finitely generated modules over PIDs are finitely generated again. Let a_1, \dots, a_n be generators of $\ker \pi_A$. Then define

$$\phi: V := \mathcal{O}[X_1, \dots, X_n] \rightarrow A$$

via $\phi(X_i) = a_i$. We have seen in the proof of remark 2.5 that $A = \ker \pi_A \oplus \mathcal{O}$. Defining π_V via $X_i \mapsto 0 \ \forall i$ we get $V = \ker \pi_V \oplus \mathcal{O}$. ϕ then induces an isomorphism on the second component, a surjection on the first and is therefore surjective. It is clear that

$$\phi_V := \ker \pi_V / (\ker \pi_V)^2 = \mathcal{O}X_1 \oplus \dots \oplus \mathcal{O}X_n$$

is a finitely generated \mathcal{O} -module of rank n . Therefore the kernel of the projection $\phi_V \rightarrow \phi_A$ is also finitely generated of rank $n' \leq n$. Independent of n' , we can choose n possibly linearly dependent linear polynomials $\bar{f}_i \in \ker(\phi_V \rightarrow \phi_A)$ without constant term that generate $\ker \phi_V \rightarrow \phi_A$. Now consider a system

(f_1, \dots, f_n) of lifts to V and denote their maximal degree with m . All elements of $\ker \pi_A$ can be written as a linear combination of the generators a_i , so a fortiori we find linear polynomials $h_i(X_1, \dots, X_n)$ s.t. $a_i^2 = h_i(a_1, \dots, a_n)$. With these additional relations we can replace the relations f_i by modified relations

$$f_i + X_i^m h_i - X_i^{m+2}.$$

Now we see that $V/(f_1, \dots, f_n)$ is a finitely generated \mathcal{O} -module, because it is generated by the images of monomials of degree $\leq n(m+1)$. Indeed, any monomial of higher degree must contain one of the X_i at least with potence $m+2$. Then, using the relation $f_i + X_i^m h_i - X_i^{m+2}$, it can be expressed as a sum of monomials of lower degree. Therefore we get a surjection

$$\mathcal{O}[X_1, \dots, X_n]/(f_1, \dots, f_n) \rightarrow A.$$

The completion of the left side is still a finitely generated \mathcal{O} -module. Indeed, the submodule M generated by the generators of $\mathcal{O}[X_1, \dots, X_n]/(f_1, \dots, f_n)$ contains the dense subset of all polynomials in $\mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n)$. Once we can show that the \mathcal{O} -submodules generated by a single polynomial are closed in $\mathcal{O}[[X_1, \dots, X_n]]/(f_1, \dots, f_n)$, it follows that M is closed as a finite union of closed submodules. Consider the submodule $f \cdot \mathcal{O}$. For any family of elements $(F_i)_{i \in I}$ of $f \cdot \mathcal{O}$, we have a family $(x_i)_{i \in I}$ with $x_i \in \mathcal{O} \forall i \in I$ s.t. $F_i = f \cdot x_i \forall i \in I$. Then

$$\lim_{i \in I} f \cdot x_i = f \cdot \lim_{i \in I} x_i = f \cdot x \in f \cdot \mathcal{O},$$

because $x \in \mathcal{O}$ as \mathcal{O} is complete. Hence, $f \cdot \mathcal{O}$ is closed. We obtain that the finite generating set of A generates a dense and closed subset in \tilde{A} , i.e. it generates \tilde{A} . Hence, \tilde{A} is a finitely generated \mathcal{O} -module $\in \mathcal{C}_{\mathcal{O}}^{\bullet}$. From corollary 2.37 we then conclude that its flat as well and therefore is a complete intersection where the tangent space is the completion of

$$\phi_A = \phi_{V/(f_1, \dots, f_n)} = \phi_V/(\overline{f_1}, \dots, \overline{f_n}).$$

$\overline{f_1}, \dots, \overline{f_n}$ generate $\ker \phi_V \rightarrow \phi_A$. Hence, analogous to the above argumentation, they also generate the completion $\ker \phi_U \rightarrow \phi_A$. Therefore, using remark 2.9, we have an isomorphism of the tangent spaces

$$\phi_{\tilde{A}} = \phi_U/(\overline{f_1}, \dots, \overline{f_n}) \rightarrow \phi_A,$$

as desired. \square

2.9 A criterion for complete intersections

Proposition 2.54. *[DDT95, theorem 5.27] Let $A \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ be finite flat. If $\#\phi_A \leq \#(\mathcal{O}/\eta_A) < \infty$, then A is a complete intersection.*

Proof. Take the morphism $f: \tilde{A} \rightarrow A$ from lemma 2.53. As f induces an isomorphism on the tangent spaces, i.e. $\phi_{\tilde{A}} = \phi_A$, we can apply lemma 2.19 and conclude that f is surjective. By lemma 2.27 we also now that $\#\phi_{\tilde{A}} \geq \#(\mathcal{O}/\eta_{\tilde{A}})$. Starting with the assumption and then using both of the previous facts, we obtain

$$\#(\mathcal{O}/\eta_A) \geq \#\phi_A = \#\phi_{\tilde{A}} \geq \#(\mathcal{O}/\eta_{\tilde{A}}).$$

As $\tilde{A} \twoheadrightarrow A$ is surjective, we apply lemma 2.21 and deduce

$$\eta_{\tilde{A}} \subset \eta_A, \quad \#(\mathcal{O}/\eta_{\tilde{A}}) \geq \#(\mathcal{O}/\eta_A).$$

All in all, we have $\#(\mathcal{O}/\eta_A) = \#(\mathcal{O}/\eta_{\tilde{A}})$ and because of $\eta_{\tilde{A}} \subset \eta_A$ we conclude $\eta_{\tilde{A}} = \eta_A$. By proposition 2.52 it follows that f is an isomorphism. Since \tilde{A} is a complete intersection, so is A . \square

2.10 Proof of Wiles' numerical criterion

Proposition 2.55. *[DDT95, theorem 5.28] Let $R, T \in \mathcal{C}_{\mathcal{O}}^{\bullet}$ such that T is finite flat and $\phi: R \twoheadrightarrow T$ is a surjective $\mathcal{C}_{\mathcal{O}}^{\bullet}$ -morphism. If $\#\phi_R \leq \#(\mathcal{O}/\eta_T) < \infty$, then R and T are complete intersections, and ϕ is an isomorphism. A fortiori, (a) \implies (c) in theorem 2.18.*

Proof. Concatenating the inequalities from lemma 2.27, corollary 2.20 which is applicable because of the surjectivity of ϕ and from the assumption, we obtain

$$\#(\mathcal{O}/\eta_T) \leq \#\phi_T \leq \#\phi_R \leq \#(\mathcal{O}/\eta_T).$$

All inequalities must be equalities and from $\#\phi_T = \#(\mathcal{O}/\eta_T)$ we conclude with proposition 2.54 that T is a complete intersection. From $\#\phi_T = \#\phi_R$ we see that ϕ induces an isomorphism on the tangent spaces. From proposition 2.48 it follows that $\phi: R \rightarrow T$ is an isomorphism and, a fortiori R is a complete intersection as well. \square

Now we can put all results together and complete the proof of theorem 2.18.

Proof. The equivalence of (a) and (b) has been established in proposition 2.28. Corollary 2.47 shows that (c) \implies (b) in theorem 2.18. Finally, proposition 2.55 gives us the implication (a) \implies (c). \square

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