

FATE-X Statements

Formalization Contribution

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Mathematical Contribution

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Exercise (1). *Let R be a UFD with two nonassociate prime elements p and q such that every prime element is an associate of either p or q . Prove that R is a PID.*

```
import Mathlib

namespace Problem1

/--
Let  $R$  be a UFD with two nonassociate prime elements  $p$  and  $q$  such that every prime
element is an associate of either  $p$  or  $q$ . Prove that  $R$  is a PID.
-/
theorem isPrincipalIdealRing_of_associated_or_associated {R : Type} [CommRing R] [IsDomain R]
  [UniqueFactorizationMonoid R] {p q : R} (hp : Prime p) (hq : Prime q) (hpq : ¬ Associated p q)
  (h : ∀ {x : R}, Prime x → Associated x p ∨ Associated x q) :
  IsPrincipalIdealRing R := by
  sorry

end Problem1
```

Exercise (2). *Let G be a finite group and L a maximal subgroup of G . Suppose L is non-Abelian and simple. Then there exist at most two minimal normal subgroups in G .*

```
import Mathlib

namespace Problem2
```

```

/--
Let  $G$  be a finite group and  $L$  a maximal subgroup of  $G$ . Suppose  $L$  is non-Abelian and simple.
Then there exist at most two minimal normal subgroups in  $G$ .
-/
theorem card_minimal_normal_subgroup_le_2 (G : Type) [Group G] [Finite G]
  (L : Subgroup G) (h_ne_top : L ≠ ⊤) (h_maximal : IsMax (⟨L, h_ne_top⟩ : {H : Subgroup G // H ≠
    ⊤}))
  (h_simple : IsSimpleGroup L) (h_non_comm : ∃ (x y : L), x * y ≠ y * x) :
  {H : {H : Subgroup G // H.Normal} | IsMin H}.ncard ≤ 2 := by
  sorry

end Problem2

```

Exercise (3). Let H be a subgroup of finite index of a group G . Show that there exists a subset S of G , such that S is both a set of representatives of the left and the right cosets of H in G .

```

import Mathlib

namespace Problem3

/--
Let  $H$  be a subgroup of finite index of a group  $G$ . Show that there exists a subset  $S$  of  $G$ ,
such that  $S$  is both a set of representatives of the left and the right cosets of  $H$  in  $G$ .
-/
theorem exists_leftCoset_rightCoset_representative
  (G : Type) [Group G] (H : Subgroup G) [H.FiniteIndex] :
  ∃ S : Set G, Subgroup.IsComplement S H ∧ Subgroup.IsComplement H S := by
  sorry

end Problem3

```

Exercise (4). Let p be an odd prime number, and let G be a finite group of order $p(p+1)$. Assume that G does not have a normal Sylow p -subgroup. Prove that $p+1$ is a power of 2.

```

import Mathlib

namespace Problem4

/--
Let  $p$  be an odd prime number, and let  $G$  be a finite group of order  $p(p+1)$ . Assume that  $G$ 
does not have a normal Sylow  $p$ -subgroup. Prove that  $p+1$  is a power of 2.
-/
theorem add_one_eq_two_pow_of_sylow_subgroup_not_normal (p : ℕ) (h_odd : Odd p) (G : Type)
  (hp : p.Prime) [Finite G] [Group G] (h_card : Nat.card G = p * (p + 1))
  (h_sylow : ∀ (H : Sylow p G), ¬ H.Normal) : ∃ (n : ℕ), p + 1 = 2 ^ n := by
  sorry

end Problem4

```

Exercise (5). *Let p be a prime, let G be a finite p -group. Let A be a maximal normal abelian subgroup of G . Prove that A is also a maximal abelian subgroup of G .*

```
import Mathlib

namespace Problem5

/--
Let  $p$  be a prime, let  $G$  be a finite  $p$ -group. Let  $A$  be a maximal normal abelian subgroup
of  $G$ . Prove that  $A$  is also a maximal abelian subgroup of  $G$ .
-/
theorem maximal_abelian_normal_subgroup_of_p_group_is_maximal_abelian_subgroup
  (p : ℕ) (hp : p.Prime) (G : Type) [Group G] [Finite G] (h_pgroup : IsPGroup p G)
  (H : Subgroup G) (h_normal : H.Normal) (h_comm : IsMulCommutative H)
  (h_maximal_normal_abelian : ∀ (K : Subgroup G), K.Normal → IsMulCommutative K → H ≤ K → H = K) :
  ∀ (K : Subgroup G), IsMulCommutative K → H ≤ K → H = K := by
  sorry

end Problem5
```

Exercise (6). *Prove that if $\#G = 396$ then G is not simple.*

```
import Mathlib

namespace Problem6

/--
Prove that if  $\#G = 396$  then  $G$  is not simple.
-/
theorem not_isSimpleGroup_of_card_eq_396 (G : Type) [Group G]
  [Finite G] (h_card : Nat.card G = 396) : ¬ IsSimpleGroup G := by
  sorry

end Problem6
```

Exercise (7). *Prove that if $\#G = 1785$ then G is not simple.*

```
import Mathlib

namespace Problem7

/--
Prove that if  $\#G = 1785$  then  $G$  is not simple.
-/
theorem not_isSimpleGroup_of_card_eq_1785 (G : Type) [Group G]
  [Finite G] (h_card : Nat.card G = 1785) : ¬ IsSimpleGroup G := by
  sorry

end Problem7
```

Exercise (8). Let $A, B \in \mathbb{Q}^\times$ be rational numbers. Consider the quaternion ring

$$D_{A,B,\mathbb{R}} = \{a + bi + cj + dk \mid a, b, c, d \in \mathbb{R}\}$$

in which the multiplication satisfies relations: $i^2 = A$, $j^2 = B$, and $ij = -ji = k$.

Show that $D_{A,B,\mathbb{R}}$ is either isomorphic to \mathbb{H} (Hamilton quaternion) or isomorphic to $\text{Mat}_{2 \times 2}(\mathbb{R})$ as \mathbb{R} -algebras.

```
import Mathlib

namespace Problem8

open Quaternion

/--
Let  $A, B \in \mathbb{Q}^\times$  be rational numbers. Consider the quaternion ring
 $D_{A,B,\mathbb{R}} = \{a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k} \mid a, b, c, d \in \mathbb{R}\}$ 
in which the multiplication satisfies relations:  $\mathbf{i}^2 = A$ ,  $\mathbf{j}^2 = B$ ,
and  $\mathbf{i}\mathbf{j} = -\mathbf{j}\mathbf{i} = \mathbf{k}$ .
Show that  $D_{A,B,\mathbb{R}}$  is either isomorphic to  $\mathbb{H}$  (Hamilton quaternion) or
isomorphic to  $\text{Mat}_{2 \times 2}(\mathbb{R})$  as  $\mathbb{R}$ -algebras.
-/
theorem quaternionAlgebra_isomorphic_to_matrix_ring_or_quaternion_ring
  (A B : ℚ) (ha : A ≠ 0) (hb : B ≠ 0) :
  ((Nonempty (H[R, A, B] ≃a[R] H[R, -1, -1])) ∨ (Nonempty (H[R, A, B] ≃a[R] Matrix (Fin 2) (Fin 2)
    R)))
  ∧ IsEmpty (Matrix (Fin 2) (Fin 2) R ≃a[R] H[R, -1, -1]) := by
  sorry

end Problem8
```

Exercise (9). Let G be a finite group and let $\text{Syl}_p(G)$ denote its set of Sylow p -subgroups. Suppose that S and T are distinct members of $\text{Syl}_p(G)$ chosen so that $\#(S \cap T)$ is maximal among all such intersections. Prove that the normalizer $N_G(S \cap T)$ does not admit normal Sylow p -subgroup.

```
import Mathlib

namespace Problem9

/--
Let  $G$  be a finite group and let  $\text{Syl}_p(G)$  denote its set of Sylow  $p$ -subgroups.
Suppose that  $S$  and  $T$  are distinct members of
 $\text{Syl}_p(G)$  chosen so that  $\#(S \cap T)$  is maximal
among all such intersections. Prove that the normalizer  $N_G(S \cap T)$  does not admit normal
Sylow  $p$ -subgroup.
-/
theorem sylow_subgroup_not_normal_of_maximal_intersection (G : Type) [Finite G] [Group G]
```

```

    (p : ℕ) [Fact (Nat.Prime p)] (S T : Sylow p G) (h_ne : S ≠ T)
    (h_maximal : ∀ (S' T' : Sylow p G), S' ≠ T' →
    ((S' : Set G) ∩ T').ncard ≤ ((S : Set G) ∩ T).ncard) :
    ∀ (P : Sylow p ((S : Subgroup G) ∩ T).normalizer), ¬ P.Normal := by
    sorry
end Problem9

```

Exercise (10). Let $A = \mathbb{R}[X, Y]/(X^2 + Y^2 + 1)$. Then it is a principal ideal domain.

```

import Mathlib

namespace Problem10

/--
Let  $A = \mathbb{R}[X, Y]/(X^2 + Y^2 + 1)$ . Then it is a principal ideal domain.
-/
theorem isPrincipalIdealRing_quot_X_pow_two_plus_Y_pow_two_plus_one :
  IsPrincipalIdealRing ((MvPolynomial (Fin 2) ℝ) /
  Ideal.span {(.X 0 ^ 2 + .X 1 ^ 2 + .C 1 : (MvPolynomial (Fin 2) ℝ))}) := by
  sorry
end Problem10

```

Exercise (11). Let $A = \mathbb{R}[X, Y]/(X^2 + Y^2 + 1)$. Then it is not a Euclidean domain.

```

import Mathlib

namespace Problem11

/--
Definition of a Euclidean norm taking value in  $\mathbb{N}$ .
-/
class EuclideanNormNat (R : Type) [CommRing R] extends Nontrivial R where
  quotient : R → R → R
  quotient_zero : ∀ a, quotient a 0 = 0
  remainder : R → R → R
  quotient_mul_add_remainder_eq : ∀ a b, b * quotient a b + remainder a b = a
  norm : R → ℕ
  remainder_lt : ∀ (a) {b}, b ≠ 0 → norm (remainder a b) < norm b
  mul_left_not_lt : ∀ (a) {b}, b ≠ 0 → ¬ norm (a * b) < norm a

/--
Let  $A = \mathbb{R}[X, Y]/(X^2 + Y^2 + 1)$ . Then it is not a Euclidean domain.
-/
theorem not_isomorphic_euclideanDomain : IsEmpty <| EuclideanNormNat ((MvPolynomial (Fin 2) ℝ) /
  Ideal.span {(.X 0 ^ 2 + .X 1 ^ 2 + .C 1 : MvPolynomial (Fin 2) ℝ)}) := by
  sorry
end Problem11

```

Exercise (12). Prove that the ring $\mathbb{Z}[\frac{1+\sqrt{-19}}{2}]$ is a principal ideal domain.

```
import Mathlib

namespace Problem12

/--
Prove that the ring  $\mathbb{Z}[\frac{1+\sqrt{-19}}{2}]$  is a principal ideal domain.
-/
theorem isPrincipalIdealRing_of_quadratic_integer_19 :
  IsPrincipalIdealRing (Algebra.adjoin  $\mathbb{Z} \{(1 + (\text{Real.sqrt } 19) * \text{Complex.I}) / 2\}$ )  $\wedge$  IsDomain
    (Algebra.adjoin  $\mathbb{Z} \{(1 + (\text{Real.sqrt } 19) * \text{Complex.I}) / 2\}$ ) := by
  sorry

end Problem12
```

Exercise (13). Let $(R, +, \cdot)$ be a (not necessarily commutative) ring. If we know that R is not a field and $x^2 = x$ for any $x \in R$, where x is not invertible. Prove that $x^2 = x$ for any x .

```
import Mathlib

namespace Problem13

/--
Let  $(R, +, \cdot)$  be a (not necessarily commutative) ring.
If we know that  $R$  is not a field and  $x^2 = x$  for any  $x \in R$ ,
where  $x$  is not invertible. Prove that  $x^2 = x$  for any  $x \in R$ .
-/
theorem sq_eq_self_of_not_unit {R : Type} [Ring R] (h :  $\neg$  IsField R)
  (h2 :  $\forall x : R, \neg \text{IsUnit } x \rightarrow x^2 = x$ ) (x : R) :  $x^2 = x$  := by
  sorry

end Problem13
```

Exercise (14). Show that if R is a unique factorization domain such that the quotient field of R is isomorphic to \mathbb{R} , then R is isomorphic to \mathbb{R} .

```
import Mathlib

namespace Problem14

/--
Show that if  $R$  is a unique factorization domain such that the quotient field of  $R$  is isomorphic
to  $\mathbb{R}$ , then  $R$  is isomorphic to  $\mathbb{R}$ .
-/
theorem isomorphic_real_of_fractionRing_isomorphic_real_of_UFD (R : Type) [CommRing R] [IsDomain R]
  [UniqueFactorizationMonoid R] (h : Nonempty ((FractionRing R)  $\simeq^*$   $\mathbb{R}$ )) :
  Nonempty (R  $\simeq^*$   $\mathbb{R}$ ) := by
  sorry
```

end Problem14

Exercise (15). Let p, q, r be three distinct prime numbers, t a positive integer. Let G be a finite group, H a normal subgroup of G such that the cardinality of G/H is r^t . Suppose that there exists a composition series

$$\{e\} = H_0 \triangleleft H_1 \triangleleft \cdots \triangleleft H_n = H,$$

of H that satisfies $n = 2$, $H_1/H_0 = \mathbb{Z}/p\mathbb{Z}$, $H_2/H_1 = \mathbb{Z}/q\mathbb{Z}$. Further suppose that there exists a composition series

$$\{e\} = G_0 \triangleleft G_1 \triangleleft \cdots \triangleleft G_n = G,$$

and positive integers $i < j \leq n$ such that $G_i/G_{i-1} = \mathbb{Z}/q\mathbb{Z}$, $G_j/G_{j-1} = \mathbb{Z}/p\mathbb{Z}$. Show that there exists a composition series

$$\{e\} = H_0 \triangleleft H_1 \triangleleft \cdots \triangleleft H_n = H,$$

of H that satisfies $n = 2$, $H_1/H_0 = \mathbb{Z}/q\mathbb{Z}$, $H_2/H_1 = \mathbb{Z}/p\mathbb{Z}$.

```
import Mathlib

namespace Problem15

/--
A subgroup `H1` is a maximal normal subgroup of `H2` if it is contained in `H2`,
and `H1` is maximal normal in `H2`.
-/
structure Subgroup.IsMaximalNormal {G : Type} [Group G] (H1 H2 : Subgroup G) : Prop where
  le : H1 ≤ H2
  subgroupOf_normal : (H1.subgroupOf H2).Normal
  is_maximal : ∀ H : Subgroup G, H1 ≤ H → H ≤ H2 → (H.subgroupOf H2).Normal → (H = H1 ∨ H = H2)

/--
A normal subgroup composition series of a group `G` is a *maximal* finite chain of normal subgroups
\[
\{e\} = G_0 \triangleleft G_1 \triangleleft \cdots \triangleleft G_n = G
\]
such that each quotient `G_{i+1}/G_i` is a simple group.
-/
structure NormalSubgroupCompositionSeries (G : Type) [Group G] : Type where
  toRelSeries : RelSeries (Subgroup.IsMaximalNormal (G := G))
  maximal : ∀ s : RelSeries (Subgroup.IsMaximalNormal (G := G)), s.length ≤ toRelSeries.length

/--
The `(i)`-th factor of a normal subgroup composition series, which is the quotient of the `(i + 1)`-th
subgroup by the previous one.
-/
def StepwiseQuotient {G : Type} [Group G] (s : NormalSubgroupCompositionSeries G) (i : Fin
  s.toRelSeries.length) :
```

```

    Type :=
    s.toRelSeries i.succ / (s.toRelSeries i.castSucc).subgroupOf _

/--
The  $(i)$ -th factor of a normal subgroup composition series is a group.
-/
instance {G : Type} [Group G] (s : NormalSubgroupCompositionSeries G) (i : Fin s.toRelSeries.length) :
  Group (StepwiseQuotient s i) := QuotientGroup.Quotient.group _ (nN := (s.toRelSeries.step
    i).subgroupOf_normal)

/--
Let  $p, q, r$  be three distinct prime numbers,  $t$  a positive integer. Let  $G$  be a finite group,
 $H$  a normal subgroup of  $G$  such that the cardinality of  $G/H$  is  $r^t$ .
Suppose that there exists a composition series

$$\{e\} = H_0 \triangleleft H_1 \triangleleft \cdots \triangleleft H_n = H,$$

of  $H$  that satisfies  $n=2$ ,  $H_1/H_0 = \mathbb{Z}/p\mathbb{Z}$ ,
 $H_2/H_1 = \mathbb{Z}/q\mathbb{Z}$ . Further suppose that there exists a composition series

$$\{e\} = G_0 \triangleleft G_1 \triangleleft \cdots \triangleleft G_n = G,$$

and positive integers  $i < j \leq n$  such that  $G_i/G_{i-1} = \mathbb{Z}/q\mathbb{Z}$ ,
 $G_j/G_{j-1} = \mathbb{Z}/p\mathbb{Z}$ . Show that there exists a composition series

$$\{e\} = H_0 \triangleleft H_1 \triangleleft \cdots \triangleleft H_n = H,$$

of  $H$  that satisfies  $n=2$ ,  $H_1/H_0 = \mathbb{Z}/q\mathbb{Z}$ ,
 $H_2/H_1 = \mathbb{Z}/p\mathbb{Z}$ .
-/
theorem exists_swap_stepwiseQuotient {p q r t : ℕ} (hp : p.Prime) (hq : q.Prime) (hr : r.Prime)
  (ht : 0 < t) (G : Type) [Group G] [Fintype G] (H : Subgroup G) [H.Normal]
  (hH : Nat.card (G / H) = r ^ t) (Hs : NormalSubgroupCompositionSeries H)
  (hHs : Hs.toRelSeries.length = 2) (hHs0 : StepwiseQuotient Hs ⟨0, by omega⟩ ≈* ZMod p)
  (hHs1 : StepwiseQuotient Hs ⟨1, by omega⟩ ≈* ZMod q)
  (Gs : NormalSubgroupCompositionSeries G) (i j : Fin Gs.toRelSeries.length) (hij : i < j)
  (hGi : StepwiseQuotient Gs i ≈* ZMod q) (hGj : StepwiseQuotient Gs j ≈* ZMod p) :
  ∃ (Hs' : NormalSubgroupCompositionSeries H) (hlen : Hs'.toRelSeries.length = 2),
  Nonempty (StepwiseQuotient Hs' ⟨0, by omega⟩ ≈* ZMod q) ∧
  Nonempty (StepwiseQuotient Hs' ⟨1, by omega⟩ ≈* ZMod p) := by
  sorry

end Problem15

```

Exercise (16). Let p be a prime and let F be a field. Let K be a finite Galois extension of F whose Galois group is a p -group (i.e., the degree $[K : F]$ is a power of p). Such an extension is called a p -extension (note that p -extensions are Galois by definition). Let L be a p -extension of K . Prove that the Galois closure of L over F is a p -extension of F .

```
import Mathlib
```

```

namespace Problem16

/--
A Galois extension such that the degree of the extension is a power of a prime  $(p)$  is
called a  $p$ -extension.
-/
class IsPEExtension (F E : Type) [Field F] [Field E] [Algebra F E]
  (p : ℕ) : Prop extends IsGalois F E where
    rank_eq_pow : ∃ (n : ℕ), Module.rank F E = p ^ n

/--
Let  $p$  be a prime and let  $F$  be a field.
Let  $K$  be a finite Galois extension of  $F$  whose Galois group is a  $p$ -group (i.e., the degree
 $[K : F]$  is a power of  $p$ ). Such an extension is called a  $p$ -extension (note that
 $p$ -extensions are Galois by definition). Let  $L$  be a  $p$ -extension of  $K$ . Prove that the
Galois closure of  $L$  over  $F$  is a  $p$ -extension of  $F$ .
-/
theorem normalClosure_isPEExtension_of_isPEExtension (F E : Type) [Field F] [Field E]
  [Algebra F E] (L : IntermediateField F E) (K : IntermediateField F L) (p : ℕ) (hp : p.Prime)
  [IsPEExtension F K p] [IsGalois K L] [IsPEExtension K L p]
  (h_normalClosure : IsNormalClosure F L E) : IsPEExtension F E p := by
  sorry

end Problem16

```

Exercise (17). Let K be a subfield of \mathbb{C} maximal with respect to the property that $\sqrt{2} \notin K$. Deduce that $[\mathbb{C} : K]$ is countable (and not finite).

```

import Mathlib

namespace Problem17

/--
Let  $K$  be a subfield of  $\mathbb{C}$  maximal with respect to the property that  $\sqrt{2} \notin K$ .
Deduce that  $[\mathbb{C} : K]$  is countable (and not finite).
-/
theorem countable_index_of_maximal_subfield_sqrt_2_nmem
  (K : Subfield ℂ) (h_nmem : (Real.sqrt 2 : ℂ) ∉ K)
  (h : ∀ (L : Subfield ℂ), K ≤ L → (Real.sqrt 2 : ℂ) ∉ L → K = L) :
  Module.rank K ℂ = Cardinal.aleph0 := by
  sorry

end Problem17

```

Exercise (18). Let E be a subfield of \mathbb{R} and let K/E be a finite Galois extension of odd degree > 1 . Prove that K cannot be E -embedded into a radical tower that is a subfield of \mathbb{R} .

```

import Mathlib

```

```

namespace Problem18

/--
Let  $(E)$  be a commutative ring,  $(F)$  be an  $(E)$ -algebra, then we say  $(F)$  is
a radical extension over  $(E)$ , if  $(F)$  is generated by a single element  $(x \in F)$ 
over  $(E)$  such that  $(x^n - e = 0)$  for some  $(e \in E)$ .
-/
def IsRadicalExtension (E F : Type) [CommRing E] [CommRing F] [Algebra E F] : Prop :=
   $\exists (x : F), \text{Algebra.adjoin } E \{x\} = \tau \wedge (\exists (n : \mathbb{N}) (e : E), n \geq 1 \wedge x^n - (\text{algebraMap } E F) e = 0)$ 

/--
An algebra is said to be a radical tower over the base ring if it can be written as
composition of radical extensions.
-/
inductive IsRadicalTower :  $\forall (E : \text{Type}) (F : \text{Type}) [\text{CommRing } E] [\text{CommRing } F] [\text{Algebra } E F], \text{Prop}$ 
  | of_isRadicalExtension (E : Type) (F : Type)
    [CommRing E] [CommRing F] [Algebra E F] : IsRadicalExtension E F  $\rightarrow$  IsRadicalTower E F
  | of_composition (E : Type) (F : Type) [CommRing E] [CommRing F] [Algebra E F] (F' : Subalgebra E F) :
    IsRadicalExtension F' F  $\rightarrow$  IsRadicalTower E F'  $\rightarrow$  IsRadicalTower E F

/--
Let  $(E)$  be a subfield of  $(\mathbb{R})$  and let  $(K/E)$  be a finite Galois extension of
odd degree  $( > 1)$ . Prove that  $(K)$  cannot be  $(E)$ -embedded into a radical tower that is
a subfield of  $(\mathbb{R})$ .
-/
theorem isEmpty_embedding_intermediateField_of_odd_degree_galois (E : Subfield  $\mathbb{R}$ ) (K : Type)
  [Field K] [Algebra E K] [IsGalois E K] (n :  $\mathbb{N}$ ) (h_odd : Odd n) (hn :  $n > 1$ ) (h_deg_eq :
    Module.rank E K = n)
  (K' : IntermediateField E  $\mathbb{R}$ ) (h_radical : IsRadicalTower E K') :
    IsEmpty (K  $\rightarrow_a$  [E] K') := by
  sorry

end Problem18

```

Exercise (19). Let $\alpha = \sqrt{(2 + \sqrt{2})(3 + \sqrt{3})}$ and consider the extension $E = \mathbb{Q}(\alpha)$. Show that $\text{Gal}(E/\mathbb{Q}) \cong Q_8$, the quaternion group of order 8.

```

import Mathlib

namespace Problem19

/--
Let  $E$  denote the algebra  $\mathbb{Q}(\sqrt{(2+\sqrt{2})(3+\sqrt{3})})$ 
-/
abbrev E : Type := (Algebra.adjoin  $\mathbb{Q}$  {Real.sqrt ((2 + Real.sqrt 2) * (3 + Real.sqrt 3))})

/--
Let  $\alpha = \sqrt{(2+\sqrt{2})(3+\sqrt{3})}$  and consider the extension  $E = \mathbb{Q}(\alpha)$ .
Show that  $\text{Gal}(E/\mathbb{Q}) \cong Q_8$ , the quaternion group of order 8.

```

```

-/
theorem galoisGroup_iso_quaternion_group : Nonempty ((E  $\simeq_a[\mathbb{Q}]$  E)  $\simeq^*$  (QuaternionGroup 2)) := by
  sorry

end Problem19

```

Exercise (20). Let p be a prime number. Let L/K be a finite extension of fields of characteristic p , and let $\sigma : x \mapsto x^p$ denote the p -Frobenius endomorphism on L , which of course stabilizes K . Prove that if $[L : K\sigma(L)] \leq p$, then L/K can be generated by one element.

```

import Mathlib

namespace Problem20

/--
Let  $p$  be a prime number. Let  $L/K$  be a finite extension of fields of characteristic  $p$ ,
and let  $\sigma : x \mapsto x^p$  denote the  $p$ -Frobenius endomorphism on  $L$ , which of course
stabilizes  $K$ . Prove that if  $[L : K\sigma(L)] \leq p$ , then  $L/K$  can be generated by one element.
-/
theorem generated_single_elem_of_degree_le_p (p : ℕ) [Fact (Nat.Prime p)]
  (K L : Type) [Field K] [Field L] [CharP L p] [Algebra K L] [FiniteDimensional K L]
  (h : Module.rank (IntermediateField.adjoin K ((frobenius L p).range : Set L)) L ≤ p) :
  ∃ (x : L), IntermediateField.adjoin K {x} = L := by
  sorry

end Problem20

```

Exercise (21). Let F be a field and let $f(x) \in F[x]$ be an irreducible polynomial. Suppose that K is a splitting field for $f(x)$ over F and assume that there exists an element $\alpha \in K$ such that both α and $\alpha + 1$ are roots of $f(x)$. Prove that there exists an intermediate field E between K and F such that $[K : E]$ is equal to the characteristic of F . (In particular, the characteristic of F is not zero)

```

import Mathlib

namespace Problem21

open Polynomial

/--
Let  $F$  be a field and let  $f(x) \in F[x]$  be an irreducible polynomial.
Suppose that  $K$  is a splitting field for  $f(x)$  over  $F$  and assume that there exists an element
 $\alpha \in K$  such that both  $\alpha$  and  $\alpha + 1$  are roots of  $f(x)$ .
Prove that there exists an intermediate field  $E$  between  $K$  and  $F$  such that  $[K : E]$ 
is equal to the characteristic of  $F$ . (In particular, the characteristic of  $F$  is not zero)
-/
theorem intermediateField_rank_eq_ringChar (F : Type) [Field F] (f : Polynomial F) (hf : Irreducible f)
  (K : Type) [Field K] [Algebra F K] (hK : f.IsSplittingField F K) ( $\alpha$  : K)

```

```

    (hα : f.aeval α = 0) (hα1 : f.aeval (α + 1) = 0) :
    ∃ (E : IntermediateField F K), Module.rank E K = ringChar F := by
  sorry
end Problem21

```

Exercise (22). Let F be a field with $\mathbb{Q} \subseteq F \subseteq \mathbb{C}$, where F/\mathbb{Q} is a finite abelian Galois extension. Prove that F contains only finitely many algebraic integers (i.e. elements in F whose minimal polynomial over \mathbb{Q} have coefficients in \mathbb{Z}) having absolute value 1, and each of the algebraic integers is a root of unity.

```

import Mathlib

namespace Problem22

/--
Let  $F$  be a field with  $\mathbb{Q} \subseteq F \subseteq \mathbb{C}$ , where  $F/\mathbb{Q}$ 
is a finite \emph{abelian} Galois extension. Prove that  $F$  contains only finitely many algebraic
integers (i.e. elements in  $F$  whose minimal polynomial over  $\mathbb{Q}$  have coefficients in
 $\mathbb{Z}$ ) having absolute value 1, and each of the algebraic integers is a root of unity.
-/
theorem finite_algebraic_integers_of_finite_module
  (F : IntermediateField ℚ ℂ) (h_fin : Module.Finite ℚ F) [IsGalois ℚ F]
  (h : IsMulCommutative (F ≃a [ℚ] F)) : {x : F | IsIntegral ℤ x ∧ ‖(x : ℂ)‖ = 1}.Finite ∧
  (∀ x : F, IsIntegral ℤ x → ‖(x : ℂ)‖ = 1 → ∃ n, x ^ n = 1) := by
  sorry
end Problem22

```

Exercise (23). Let $f(X) \in \mathbb{Z}[X]$ be an irreducible polynomial, n_p is the number of solutions of $f(X)$ in \mathbb{F}_p , show that

$$\lim_{s \rightarrow 1^+} \frac{\sum_{p \text{ prime}} \frac{n_p}{p^s}}{\sum_{p \text{ prime}} \frac{1}{p^s}} = 1$$

```

import Mathlib

namespace Problem23

local instance (p : Nat.Primes) : NeZero p.1 := ⟨p.2.ne_zero⟩
local instance (p : Nat.Primes) : IsDomain (ZMod p) := @ZMod.instIsDomain p ⟨p.2⟩

/--
Let  $f(X) \in \mathbb{Z}[X]$  be an irreducible polynomial,  $n_p$  is the number of solutions of
 $f(X)$  in  $\mathbb{F}_p$ , show that  $\lim_{s \rightarrow 1^+} \frac{\sum_{p \text{ prime}} \frac{n_p}{p^s}}{\sum_{p \text{ prime}} \frac{1}{p^s}} = 1$ .
-/

```

```

-/
theorem ratio_tendsto_one_of_irreducible (f : Polynomial ℤ) (h_irr : Irreducible f) :
  Function.rightLim
    (fun (s : ℝ) ↦
      (tsum (fun p : Nat.Primes ↦ (f.rootSet (ZMod p)).ncard * ((p : ℝ) ^ (-s)))) /
      (tsum (fun p : Nat.Primes ↦ (p : ℝ) ^ (-s)))) 1 = 1 := by
  sorry
end Problem23

```

Exercise (24). Let p_1, \dots, p_r be r different prime numbers. Prove that the Galois group of $K = \mathbb{Q}(\sqrt{p_1}, \dots, \sqrt{p_r})$ over \mathbb{Q} is $(\mathbb{Z}/2\mathbb{Z})^r$, here $\mathbb{Z}/2\mathbb{Z}$ is the cyclic group of order 2.

```

import Mathlib

namespace Problem24

/--
The field  $K = \mathbb{Q}(\sqrt{p_1}, \dots, \sqrt{p_r})$ 
for a finite list of integers  $p_1, \dots, p_r$ .
-/
abbrev RatAdjoinSqrt {I : Type} (p : I → ℕ) : Type :=
  Algebra.adjoin ℚ (Set.range (fun i ↦ Real.sqrt (p i)))

/--
Let  $p_1, \dots, p_r$  be  $r$  different prime numbers.
Prove that the Galois group of  $K = \mathbb{Q}(\sqrt{p_1}, \dots, \sqrt{p_r})$  over  $\mathbb{Q}$ 
is  $(\mathbb{Z}/2\mathbb{Z})^r$ , here  $\mathbb{Z}/2\mathbb{Z}$  is the cyclic group of order 2.
-/
theorem galoisGroup_iso_of_distinct_primes {I : Type} [Finite I] (p : I → ℕ)
  (hp : ∀ (i : I), (p i).Prime) (h_inj : p.Injective) :
  Nonempty ((RatAdjoinSqrt p ≃α[ℚ] RatAdjoinSqrt p) ≃* (Multiplicative (I → (ZMod 2)))) := by
  sorry
end Problem24

```

Exercise (25). Prove that the automorphism group of $\mathbb{F}_2(t)$ is isomorphic to S_3 , and its fixed field is $\mathbb{F}_2(u)$ with

$$u = \frac{(t^4 - t)^3}{(t^2 - t)^5} = \frac{(t^2 + t + 1)^3}{(t^2 - t)^2}$$

```

import Mathlib

namespace Problem25

/--
Prove that the automorphism group of  $\mathbb{F}_2(t)$  is isomorphic to  $S_3$ , and its fixed field is
 $\mathbb{F}_2(u)$  with  $u = \frac{(t^4 - t)^3}{(t^2 - t)^5} = \frac{(t^2 + t + 1)^3}{(t^2 - t)^2}$ .

```

```

-/
theorem fixedField_eq_algebra_adjoin :
  Nonempty ((RatFunc (ZMod 2) ≃+* RatFunc (ZMod 2)) ≃* (Equiv.Perm (Fin 3))) ^
  IntermediateField.fixedField (F := ZMod 2) (E := RatFunc (ZMod 2)) τ =
  IntermediateField.adjoin (ZMod 2) {((.X ^ 4 - .X) ^ 3 / (.X ^ 2 - .X) ^ 5 : (RatFunc (ZMod 2)))}
  := by
  sorry
end Problem25

```

Exercise (26). Let K/\mathbb{Q} be a finite extension. Let H be a closed subgroup of the absolute Galois group $G(K)$ of K . If H is finite, then the cardinality of H is either one or two.

```

import Mathlib

namespace Problem26

/--
Let  $K/\mathbb{Q}$  be a finite extension.
Let  $H$  be a closed subgroup of the absolute Galois group  $G(K)$  of  $K$ .
If  $H$  is finite, then the cardinality of  $H$  is either one or two.
-/
theorem card_one_or_two_of_finite_closed_subgroup_of_absoluteGaloisGroup
  (K : Type) [Field K] [Algebra ℚ K] [Module.Finite ℚ K]
  (H : Subgroup (Field.absoluteGaloisGroup K))
  (h_closed : IsClosed (H : Set (Field.absoluteGaloisGroup K)))
  (h_fin : Finite H) : Nat.card H = 1 ∨ Nat.card H = 2 := by
  sorry
end Problem26

```

Exercise (27). Let p be a prime number. Let K/\mathbb{Q} be a finite extension, such that the p^2 th root of unity is contained in K . Let L/K be a Galois extension of degree p , show that there exists a Galois extension L'/L of degree p , such that the extension L'/K is Galois.

```

import Mathlib

namespace Problem27

/--
Let  $p$  be a prime number. Let  $K/\mathbb{Q}$  be a finite extension, such that the  $p^2$ th
root of unity is contained in  $K$ . Let  $L/K$  be a Galois extension of degree  $p$ , show that there
exists a Galois extension  $L'/L$  of degree  $p$ , such that the extension  $L'/K$  is Galois.
-/
theorem isGalois_and_rank_eq_of_isPrimitiveRoot_sq (p : ℕ) (hp : p.Prime) {K : Type} [Field K]
  [NumberField K] {ζ : K} (h : IsPrimitiveRoot ζ (p^2))
  {L : IntermediateField K (AlgebraicClosure K)} [IsGalois K L]
  (hdeg : Module.rank K L = p) :
  ∃ (L' : Type) (ι : Field L') (ι : Algebra K L')

```

```

    ( _ : Algebra L L' ) ( _ : IsScalarTower K L L' ),
    IsGalois K L' ^ IsGalois L L' ^ Module.rank L L' = p := by
  sorry
end Problem27

```

Exercise (28). Let K/\mathbb{Q} be a finite extension. Let g be a nontrivial element of the absolute Galois group $G(K)$ of K . Show that g admits an infinite number of conjugates.

```

import Mathlib

namespace Problem28

/--
Let  $K/\mathbb{Q}$  be a finite extension.
Let  $g$  be a nontrivial element of the absolute Galois group  $G(K)$  of  $K$ .
Show that  $g$  admits an infinite number of conjugates.
-/
theorem infinite_conj_of_ne_1_absoluteGaloisGroup (K : Type)
  [Field K] [Algebra  $\mathbb{Q}$  K] [Module.Finite  $\mathbb{Q}$  K] (g : Field.absoluteGaloisGroup K) (h : g ≠ 1) :
  {g' : Field.absoluteGaloisGroup K | IsConj g g'}.Infinite := by
  sorry
end Problem28

```

Exercise (29). Let K/\mathbb{Q} be a finite extension. Let g be an element of the absolute Galois group $G(K)$ of K . Show that the subgroup generated by g is closed in $G(K)$ if and only if g is torsion.

```

import Mathlib

namespace Problem29

/--
Let  $K/\mathbb{Q}$  be a finite extension. Let  $g$  be an element of the absolute Galois group  $G(K)$  of  $K$ . Show that the subgroup generated by  $g$  is closed in  $G(K)$  if and only if  $g$  is torsion.
-/
theorem isClosed_zpowers_iff_isOfFinOrder (K : Type)
  [Field K] [Algebra  $\mathbb{Q}$  K] [Module.Finite  $\mathbb{Q}$  K] (g : Field.absoluteGaloisGroup K) :
  IsClosed ((Subgroup.zpowers g) : Set (Field.absoluteGaloisGroup K)) ↔ IsOfFinOrder g := by
  sorry
end Problem29

```

Exercise (30). Let A be a subring of a ring B , such that the set $B \setminus A$ is closed under multiplication. Show that A is integrally closed in B .

```

import Mathlib

namespace Problem30

/--
Let  $(A \setminus)$  be a subring of a ring  $(B \setminus)$ , such that the set  $(B \setminus \setminus A \setminus)$  is closed under
multiplication. Show that  $(A \setminus)$  is integrally closed in  $(B \setminus)$ .
-/
theorem integrallyClosedIn_of_complement_multiplicatively_closed (B : Type) [CommRing B] (A : Subring
  B)
  (h :  $\forall (x \ y : B), x \notin A \rightarrow y \notin A \rightarrow x * y \notin A$ ) : IsIntegrallyClosedIn A B := by
  sorry

end Problem30

```

Exercise (31). Let $R = \mathbb{C}[x_1, \dots, x_n]/(x_1^2 + x_2^2 + \dots + x_n^2)$. Then R is a unique factorization domain for $n \geq 5$.

```

import Mathlib

namespace Problem31

open MvPolynomial

/--
Let  $(R = \mathbb{C}[x_1, \dots, x_n]/(x_1^2 + x_2^2 + \dots + x_n^2) \setminus)$ .
-/
abbrev R (n : ℕ) : Type :=
  MvPolynomial (Fin n) ℂ / Ideal.span  $\{(\sum i : \text{Fin } n, X \ i \ ^2 : \text{MvPolynomial } (\text{Fin } n) \ \mathbb{C})\}$ 

/--
Let  $(R = \mathbb{C}[x_1, \dots, x_n]/(x_1^2 + x_2^2 + \dots + x_n^2) \setminus)$ .
Then  $(R \setminus)$  is a unique factorization domain for  $(n \geq 5)$ .
-/
theorem UFD_of_ge_5 (n : ℕ) (h : n ≥ 5) :
   $\exists (h : \text{IsDomain } (R \ n)), \text{UniqueFactorizationMonoid } (R \ n)$  := by
  sorry

end Problem31

```

Exercise (32). Let A be a Noetherian local ring such that its completion \hat{A} is a unique factorization domain. Then A is a unique factorization domain.

```

import Mathlib

namespace Problem32

open IsLocalRing

```

```

/--
Let  $(A)$  be a Noetherian local ring such that its completion  $(\widehat{A})$  is a unique
factorization domain. Then  $(A)$  is a unique factorization domain.
-/
theorem UFD_of_adicCompletion_UFD (R : Type) [CommRing R] [IsLocalRing R] [IsNoetherianRing R]
  [IsDomain (AdicCompletion (maximalIdeal R) R)]
  [UniqueFactorizationMonoid (AdicCompletion (maximalIdeal R) R)] :
   $\exists$  (h : IsDomain R), UniqueFactorizationMonoid R := by
  sorry

end Problem32

```

Exercise (33). Let $A \subset B$ be commutative rings such that B is finitely generated as a module over A . If B is a noetherian ring, show that A is also a noetherian ring.

```

import Mathlib

namespace Problem33

/--
Let  $A \subset B$  be commutative rings such that  $B$  is finitely generated as a module over  $A$ .
If  $B$  is a noetherian ring, show that  $A$  is also a noetherian ring.
-/
theorem isNoetherianRing_of_fg_of_isNoetherianRing (B : Type) [CommRing B] [IsNoetherianRing B]
  (A : Subring B) (h : Module.Finite A B) : IsNoetherianRing A := by
  sorry

end Problem33

```

Exercise (34). If R is a valuation ring of Krull dimension ≥ 2 , then the formal power series ring $R[[X]]$ is not integrally closed.

```

import Mathlib

namespace Problem34

open PowerSeries

/--
If  $(R)$  is a valuation ring of Krull dimension  $\geq 2$ ,
then the formal power series ring  $(R[[X]])$  is not integrally closed.
-/
theorem powerSeries_not_integrallyClosed_of_two_lt_ringKrullDim (R : Type) [CommRing R]
  [IsDomain R] [ValuationRing R] (two_lt : 2 ≤ ringKrullDim R) :
   $\neg$  (IsIntegrallyClosed R[[X]]) := by
  sorry

end Problem34

```

Exercise (35). *A commutative ring whose prime ideals are finitely generated is Noetherian.*

```
import Mathlib

namespace Problem35

/--
A commutative ring whose prime ideals are finitely generated is Noetherian.
-/
theorem noetherian_of_prime_ideals_fg (R : Type) [CommRing R]
  (h_fg : ∀ (p : Ideal R), p.IsPrime → p.FG) : IsNoetherianRing R := by
  sorry

end Problem35
```

Exercise (36). *If R is Noetherian and M and N are finitely generated R -modules, show that*

$$\text{Ass Hom}_R(M, N) = \text{Supp } M \cap \text{Ass } N,$$

where $\text{Supp } M$ is the set of all primes containing the annihilator of M .

```
import Mathlib

namespace Problem36

/--
If  $(R)$  is Noetherian and  $(M)$  and  $(N)$  are finitely generated  $(R)$ -modules, show that
 $\text{Ass Hom}_R(M, N) = \text{Supp } M \cap \text{Ass } N$ ,
where  $\text{Supp } M$  is the set of all primes containing the annihilator of  $(M)$ .
-/
theorem associatedPrimes_hom_eq_support_inter_associatedPrimes (R : Type) [CommRing R]
  [IsNoetherianRing R] (M N : Type) [AddCommGroup M] [AddCommGroup N] [Module R M] [Module R N]
  [Module.Finite R M] [Module.Finite R N] : associatedPrimes R (M → [R] N) =
  {p | p ∈ associatedPrimes R N ∧ Module.annihilator R M ≤ p} := by
  sorry

end Problem36
```

Exercise (37). *Let $R = \mathbb{C}[x_{11}, x_{12}, \dots, x_{1n}, x_{21}, x_{22}, \dots, x_{2n}, \dots, x_{n1}, x_{n2}, \dots, x_{nn}] / (\det(x_{ij}) - 1)$, show that R is a unique factorization domain.*

```
import Mathlib

namespace Problem37

/--
Let  $R = \mathbb{C}[x_{11}, x_{12}, \dots, x_{1n}, x_{21}, x_{22}, \dots,$ 
```

```

x_{2n}, \dots, x_{n1}, x_{n2}, \dots, x_{nn}] / (\det(x_{ij}) - 1)$.
-/
abbrev QuotDetSubOne (n : ℕ) : Type := MvPolynomial ((Fin n) × (Fin n)) ℂ / Ideal.span {
  Matrix.det (fun (i : Fin n) ↦ (fun (j : Fin n) ↦ (.X ⟨i, j⟩ : (MvPolynomial ((Fin n) × (Fin
    n)) ℂ)))) - .C 1}

/--
Let  $R = \mathbb{C}[x_{11}, x_{12}, \dots, x_{1n}, x_{21}, x_{22}, \dots,$ 
 $x_{2n}, \dots, x_{n1}, x_{n2}, \dots, x_{nn}] / (\det(x_{ij}) - 1)$ ,
show that  $R$  is a unique factorization domain.
-/
theorem ufd_quotDetSubOne (n : ℕ) (h : n ≥ 1) : ∃ (h : IsDomain (QuotDetSubOne n)),
  UniqueFactorizationMonoid (QuotDetSubOne n) := by
  sorry

end Problem37

```

Exercise (38). Let k be a field, and let $R = k[t]/(t^2)$. Set

$$p(x) = tx^3 + tx^2 - x^2 - x \in R[x].$$

Show that $S = R[x]/(p)$ is a free R -module of rank 2.

```

import Mathlib

namespace Problem38

open Polynomial DualNumber

/--
Let  $(k)$  be a field, and let  $(R = k[t]/(t^2))$ . Set
 $[$ 
 $p(x) = tx^3 + tx^2 - x^2 - x \in R[x]$ .
 $]$ 
Let  $(S = R[x]/(p))$ .
-/
abbrev S (k : Type) [Field k] : Type := ((DualNumber k)[X] / Ideal.span {((C ε) * X^3 + (C ε) * X^2 -
  X^2 - X : (DualNumber k)[X])})

/--
 $(S)$  has a  $(R)$  module structure inherited from  $R[x]$ .
-/
noncomputable instance (k : Type) [Field k] : Module (DualNumber k) (S k) := Module.compHom _ C

/--
Let  $(k)$  be a field, and let  $(R = k[t]/(t^2))$ . Set
 $[$ 
 $p(x) = tx^3 + tx^2 - x^2 - x \in R[x]$ .
 $]$ 
Show that  $(S = R[x]/(p))$  is a free  $(R)$ -module of rank  $(2)$ .
-/

```

```

theorem free_dualNumber_and_rank_eq_2 (k : Type) [Field k] :
  Module.Free (DualNumber k) (S k)  $\wedge$  Module.rank (DualNumber k) (S k) = 2 := by
  sorry

end Problem38

```

Exercise (39). Let R be a normal Noetherian domain, K its fraction field, L/K a finite field extension, and \overline{R} the integral closure of R in L . Prove that only finitely many primes \mathfrak{P} of \overline{R} lie over a given prime \mathfrak{p} of R .

```

import Mathlib

namespace Problem39

/--
Let  $(R)$  be a normal Noetherian domain,  $(K)$  its fraction field,  $(L/K)$  a finite
field extension, and  $(\overline{R})$  the integral closure of  $(R)$  in  $(L)$ .
Prove that only finitely many primes  $(\mathfrak{P})$  of  $(\overline{R})$  lie over a given
prime  $(\mathfrak{p})$  of  $(R)$ .
-/
theorem finite_primes_lies_over_of_finite_extension (R : Type) [CommRing R] [IsDomain R]
  [IsNoetherianRing R] [IsIntegrallyClosed R] (L : Type) [Field L] [Algebra R L]
  [Algebra (FractionRing R) L] [IsScalarTower R (FractionRing R) L]
  [FiniteDimensional (FractionRing R) L] (p : Ideal R) [p.IsPrime] :
  (p.primesOver (integralClosure R L)).Finite := by
  sorry

end Problem39

```

Exercise (40). Let A be a reduced local ring with residue field k and finite set Σ of minimal primes. For each $\mathfrak{p} \in \Sigma$, set $K(\mathfrak{p}) = \text{Frac}(A/\mathfrak{p})$. Let P be a finitely generated module. Show that P is free of rank r if and only if $\dim_k(P \otimes_A k) = r$ and $\dim_{K(\mathfrak{p})}(P \otimes_A K(\mathfrak{p})) = r$ for each $\mathfrak{p} \in \Sigma$.

```

import Mathlib

namespace Problem40

open TensorProduct

/--
Let  $A$  be a reduced local ring with residue field  $k$  and finite set  $\Sigma$  of minimal primes.
For each  $\mathfrak{p} \in \Sigma$ , set  $K(\mathfrak{p}) = \text{Frac}(A/\mathfrak{p})$ .
Let  $P$  be a finitely generated module. Show that  $P$  is free of rank  $r$  if and only if
 $\dim_k(P \otimes_A k) = r$  and  $\dim_{K(\mathfrak{p})}(P \otimes_A K(\mathfrak{p})) = r$ 
for each  $\mathfrak{p} \in \Sigma$ .
-/
theorem free_of_rank_iff (R : Type) [CommRing R] [IsLocalRing R] [IsReduced R]
  (h : (minimalPrimes R).Finite) (r : ℕ) (M : Type) [AddCommGroup M] [Module R M] [Module.Finite R M] :

```

```

Module.Free R M ^ Module.rank R M = r ↔
(Module.rank (IsLocalRing.ResidueField R) ((IsLocalRing.ResidueField R) ⊗[R] M) = r ∧
  ∀ p ∈ minimalPrimes R,
Module.rank (FractionRing (R / p)) ((FractionRing (R / p)) ⊗[R] M) = r) := by
sorry

end Problem40

```

Exercise (41). Let k be a field, $A := k[X_1, X_2, \dots]$ a polynomial ring, $m_1 < m_2 < \dots$ positive integers with $m_{i+1} - m_i > m_i - m_{i-1}$ for $i > 1$. Set

$$\mathfrak{p}_i := (X_{m_i+1}, \dots, X_{m_{i+1}})$$

and $S := A - \bigcup_{i \geq 1} \mathfrak{p}_i$. Show that $S^{-1}A$ is noetherian with infinite krull dimension.

```

import Mathlib

namespace Problem41

/--
The multiplicative subset generated by elements
not in a given family of ideals.
-/
def compl_all {α R : Type} [CommRing R] (I : α → Ideal R) : Submonoid R :=
  Submonoid.closure (U (i : α), (I i : Set R))c

/--
The ideal generated by a set of single
variables in a multivariate polynomial ring.
-/
def ideal_x {α : Type} (R : Type) [CommRing R] (J : Set α) : Ideal (MvPolynomial α R) :=
  Ideal.span ((MvPolynomial.X)'' J)

/--
Let \(\ A := k[X_1, X_2, \dots] \).
Set \(\ \mathfrak{p}_i := (X_{m_i+1}, \dots, X_{m_{i+1}}) \) and
\(\ S := A - \bigcup_{i \geq 1} \mathfrak{p}_i \).
This is the ring \(\ S^{-1}A \).
-/
abbrev SInvA (k : Type) [Field k] (m : ℕ → ℕ) : Type := (Localization (compl_all fun (n : ℕ) ↦
  ideal_x k (Set.Ioc (m n) (m (n + 1)))))

/--
Let \(\ (k) \) be a field, \(\ (A := k[X_1, X_2, \dots]) \) a polynomial ring, \(\ (m_1 < m_2 < \dots) \)
positive integers with \(\ (m_{i+1} - m_i > m_i - m_{i-1}) \) for \(\ (i > 1) \). Set
\(\ \mathfrak{p}_i := (X_{m_i+1}, \dots, X_{m_{i+1}}) \)
and \(\ S := A - \bigcup_{i \geq 1} \mathfrak{p}_i \).
Show that \(\ (S^{-1}A) \) is noetherian with infinite krull dimension.
-/
theorem isNoetherianRing_and_krullDim_eq_top (k : Type) [Field k] (m : ℕ → ℕ) (h : StrictMono m)
  (h_diff_mono : StrictMono (fun (i : ℕ) ↦ m (i + 1) - m i)) :

```

```

    IsNoetherianRing (SInvA k m) ^
    ringKrullDim (SInvA k m) = τ := by
    sorry

end Problem41

```

Exercise (42). Let k be any field. Suppose that $A = k[[x, y]]/(f)$ and $B = k[[u, v]]/(g)$, where $f = xy$ and $g = uv + \delta$ with $\delta \in (u, v)^3$. Show that A and B are isomorphic.

```

import Mathlib

namespace Problem42

/--
Let  $(k)$  be any field. Suppose that  $(A = k[[x, y]]/(f))$  and  $(B = k[[u, v]]/(g))$ ,
where  $(f = xy)$  and  $(g = uv + \delta)$  with  $(\delta \in (u, v)^3)$ . Show that  $(A)$  and  $(B)$ 
are isomorphic.
-/
theorem nonEmpty_ringEquiv_of_sub_in_cube (k : Type) [Field k]
  (g : MvPowerSeries (Fin 2) k) (hg : g - .X 0 * .X 1 ∈ (Ideal.span {MvPowerSeries.X 0, .X 1}) ^ 3)
  :
  Nonempty (((MvPowerSeries (Fin 2) k) / Ideal.span {(.X 0 * .X 1 : (MvPowerSeries (Fin 2) k))}) ≃+
    *
    ((MvPowerSeries (Fin 2) k) / Ideal.span {g})) := by
  sorry

end Problem42

```

Exercise (43). Let A be a reduced Noetherian local ring, $\text{Char } A = p$. Show that the absolute Frobenius $F_A: A \rightarrow A, a \mapsto a^p$ is flat if and only if A is regular.

```

import Mathlib

namespace Problem43

open IsLocalRing

/--
A commutative local noetherian ring  $R$  is regular if  $\dim m/m^2 = \dim R$ .
-/
class IsRegularLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  reg : Module.finite (ResidueField R) (CotangentSpace R) = ringKrullDim R

/--
Let  $A$  be a reduced Noetherian local ring,  $\text{Char } A = p$ .
Show that the absolute Frobenius  $F_A: A \rightarrow A, a \mapsto a^p$  is flat if and only if  $A$  is
regular.
-/

```

```

theorem IsRegularLocalRing.frobenius_flat {A : Type} [CommRing A] [IsNoetherianRing A]
  [IsLocalRing A] [IsReduced A] (p : ℕ) [Fact p.Prime] [CharP A p] :
  (frobenius A p).Flat ↔ IsRegularLocalRing A := by
  sorry

end Problem43

```

Exercise (44). Let k be a field, and set $A = k[X, Y, Z]/(X^2 - Y^2, Y^2 - Z^2, XY, YZ, ZX)$. Show that A is not a global complete intersection.

```

import Mathlib

namespace Problem44

open MvPolynomial

/--
Let  $k$  be a field. Let  $S$  be a finite type  $k$ -algebra. We say that  $S$  is a
\textit{global complete intersection over  $k$ } if there exists a presentation
 $S = k[x_1, \dots, x_n]/(f_1, \dots, f_c)$  such that  $\dim(S) = n - c$ .
-/
class IsGlobalCompleteIntersection (k : Type) [Field k] (S : Type) [CommRing S] [Algebra k S] :
  Prop extends Algebra.FiniteType k S where
  isGlobalCompleteIntersection : ∃ n : ℕ, ∃ rs : List (MvPolynomial (Fin n) k),
    Nonempty (S ≃A[k] (MvPolynomial (Fin n) k) / Ideal.ofList rs) ∧ ringKrullDim S + rs.length = n

/--
Let  $(k)$  be a field, and set  $(A = k[X, Y, Z]/(X^2 - Y^2, Y^2 - Z^2, XY, YZ, ZX))$ .
Show that  $(A)$  is not a global complete intersection.
-/
theorem quot_x2_sub_y2_y2_sub_z2_xy_yz_zx_not_global_complete_intersection (k : Type) [Field k] :
  ¬ IsGlobalCompleteIntersection k (MvPolynomial (Fin 3) k / Ideal.span
    ({(X 0)^2 - (X 1)^2, (X 1)^2 - (X 2)^2, (X 0) * (X 1), (X 1) * (X 2), (X 2) * (X 0)} :
    Set (MvPolynomial (Fin 3) k))) := by
  sorry

end Problem44

```

Exercise (45). Let k be a field and $A = k[x_1, \dots, x_r]$ the polynomial ring in r variables. Let M be a graded module over A , and let

$$0 \rightarrow K \rightarrow L_{r-1} \rightarrow \cdots \rightarrow L_0 \rightarrow M \rightarrow 0$$

be an exact sequence of graded homomorphisms of graded modules, such that L_0, \dots, L_{r-1} are free. Then K is free. Gradings of modules are by $\mathbb{Z}_{\geq 0}$.

```

import Mathlib

```

```

namespace Problem45

/--
A linear map `f` between graded modules is a graded homomorphism if it respects the
grading structure.
-/
def IsGradedHom {R M N  $\iota$  : Type} [CommRing R] [AddCommGroup M] [AddCommGroup N]
  [Module R M] [Module R N] ( $\iota_1$  :  $\iota \rightarrow \text{Submodule } R \text{ } M$ ) ( $\iota_2$  :  $\iota \rightarrow \text{Submodule } R \text{ } N$ )
  (f : M  $\rightarrow$  [R] N) : Prop :=  $\forall$  (i :  $\iota$ ) (x :  $\iota_1$  i), f x  $\in$   $\iota_2$  i

/--
Let  $k$  be a field and  $A = k[x_1, \dots, x_r]$  the polynomial ring in  $r$  variables. Let  $M$  be
a graded module over  $A$ , and let
\[
0 \rightarrow L_{r-1} \rightarrow \dots \rightarrow L_0 \rightarrow M \rightarrow 0
\]
be an exact sequence of graded homomorphisms of graded modules, such that  $L_0, \dots, L_{r-1}$ 
are free. Then  $M$  is free. {Gradings of modules are by  $\mathbb{Z}_{\geq 0}$ .}
-/
theorem free_of_free_resolution {k : Type} [Field k] {r :  $\mathbb{N}$ }
  (C : ChainComplex (ModuleCat.{0} (MvPolynomial (Fin r) k))  $\mathbb{N}$ )
  (hC :  $\forall$  (n :  $\mathbb{N}$ ), n > (r + 1)  $\rightarrow$  CategoryTheory.Limits.IsZero (C.X n))
  ( $\iota_1$  :  $\forall$  (n :  $\mathbb{N}$ ), ( $\mathbb{N} \rightarrow \text{Submodule } (\text{MvPolynomial } (\text{Fin } r) \text{ } k) (C.X n)$ ))
  [hM :  $\forall$  (n :  $\mathbb{N}$ ), DirectSum.Decomposition ( $\iota_1$  n)]
  [hM' :  $\forall$  (n :  $\mathbb{N}$ ), SetLike.GradedSMul (MvPolynomial.homogeneousSubmodule (Fin r) k) ( $\iota_1$  n)]
  (h_exact : C.Acyclic)
  (h_gr :  $\forall$  (i j :  $\mathbb{N}$ ), IsGradedHom ( $\iota_1$  i) ( $\iota_1$  j) (C.d i j).hom)
  (h_free :  $\forall$  (n :  $\mathbb{N}$ ),  $1 \leq n \wedge n \leq r \rightarrow \text{Module.Free } (\text{MvPolynomial } (\text{Fin } r) \text{ } k) (C.X n)$ ) :
  Module.Free (MvPolynomial (Fin r) k) (C.X (r + 1)) := by
  sorry

end Problem45

```

Exercise (46). Let M be an R -module. Then M is flat if and only if the following condition holds: if P is a finitely presented R -module and $f : P \rightarrow M$ a R -linear map, then there is a free finite R -module F and module maps $h : P \rightarrow F$ and $g : F \rightarrow M$ such that $f = g \circ h$.

```

import Mathlib

namespace Problem46

/--
Let  $(M)$  be an  $(R)$ -module. Then  $(M)$  is flat if and only if the following condition holds:
if  $(P)$  is a finitely presented  $(R)$ -module and  $(f : P \rightarrow M)$  a  $(R)$ -linear map,
then there is a free finite  $(R)$ -module  $(F)$  and module maps  $(h : P \rightarrow F)$  and  $(g : F \rightarrow M)$ 
such that  $(f = g \circ h)$ .
-/
theorem module_flat_iff (R : Type) [CommRing R] (M : Type) [AddCommGroup M] [Module R M] :
  Module.Flat R M  $\leftrightarrow$ 
   $\forall$  P : Type,  $\forall$  ( $\iota$  : AddCommGroup P),  $\forall$  ( $\iota$  : Module R P),  $\forall$  f : P  $\rightarrow$  [R] M,
  Module.FinitePresentation R P  $\rightarrow$ 

```

```

    ∃ (F : Type) (A : AddCommGroup F) (M : Module R F), Module.Finite R F ∧ Module.Free R F ∧
    ∃ h : P → [R] F, ∃ g : F → [R] M, f = g.comp h := by
  sorry
end Problem46

```

Exercise (47). Show that the ring $A = k[x, y]/(y^2 - f(x))$ is a Dedekind domain and the class group of the ring A is not trivial, where k is a field of characteristic not 2, $f(x) = (x - t_1) \dots (x - t_n)$ with $t_1, \dots, t_n \in k$ distinct and $n \geq 3$ is an odd integer.

```

import Mathlib

namespace Problem47

/--
The ring  $(A = k[x, y]/(y^2 - f(x)))$ ,
where  $(k)$  is a field and  $(f(x) = (x - t_1) \dots (x - t_n))$ .
-/
abbrev A {k : Type} [Field k] {n : ℕ} (t : (Fin n) → k) : Type := (MvPolynomial (Fin 2) k) /
  Ideal.span {(X 1 ^ 2) - ∏ (m : Fin n), (X 0 - C (t m)) : (MvPolynomial (Fin 2) k)}

/--
Show that the ring  $(A = k[x, y]/(y^2 - f(x)))$  is a Dedekind domain and the class group of the
ring  $(A)$  is not trivial, where  $(k)$  is a field of characteristic not 2,
 $(f(x) = (x - t_1) \dots (x - t_n))$  with  $(t_1, \dots, t_n \in k)$  distinct and
 $(n \geq 3)$  is an odd integer.
-/
theorem isEmpty_isomorphism_UFD_of_quotient (k : Type) [Field k] (h_char : ¬ CharP k 2)
  (n : ℕ) (h_ge : n ≥ 3) (h_odd : Odd n) (t : (Fin n) → k) (h_inj : Function.Injective t) :
  ∃ _ : IsDedekindDomain (A t), Nontrivial (ClassGroup (A t)) := by
  sorry
end Problem47

```

Exercise (48). A commutative ring A is absolutely flat if every A -module is flat. Prove that A is absolutely flat if and only if every principal ideal is idempotent.

```

import Mathlib

namespace Problem48

/--
A commutative ring  $(A)$  is absolutely flat if every  $(A)$ -module is flat.
-/
class IsAbsolutelyFlat (R : Type) [CommRing R] : Prop where
  out {P : Type} [AddCommGroup P] [Module R P] : Module.Flat R P

/--

```

```

Prove that  $\backslash(A \backslash)$  is absolutely flat if and only if every principal ideal is idempotent.
-/
theorem isAbsolutelyFlat_iff_principal_ideal_idempotent (R : Type) [CommRing R] :
  IsAbsolutelyFlat R  $\leftrightarrow$  ( $\forall I : \text{Ideal } R, I.\text{IsPrincipal} \rightarrow I^2 = I$ ) := by
  sorry
end Problem48

```

Exercise (49). Let A be a commutative ring. Prove that every principal ideal of A is idempotent if and only if every finitely generated ideal is a direct summand of A .

```

import Mathlib

namespace Problem49

/--
Let  $\backslash(A \backslash)$  be a commutative ring. Prove that every principal ideal of  $\backslash(A \backslash)$  is idempotent
if and only if every finitely generated ideal is a direct summand of  $\backslash(A \backslash)$ .
-/
theorem principal_ideal_idempotent_iff_fg_ideal_is_direct_summand (A : Type) [CommRing A] :
  ( $\forall I : \text{Ideal } A, I.\text{IsPrincipal} \rightarrow I^2 = I$ )  $\leftrightarrow$ 
  ( $\forall I : \text{Ideal } A, I.\text{FG} \rightarrow (\exists J : \text{Ideal } A, I \cup J = \top \wedge I \cap J = \perp)$ ) := by
  sorry
end Problem49

```

Exercise (50). Let (A, \mathfrak{m}, K) be a complete local ring containing a field, and suppose that \mathfrak{m} is finitely generated over A . Then A is Noetherian.

```

import Mathlib

namespace Problem50

/--
Let  $\backslash((A, \mathfrak{m}, K))$  be a complete local ring containing a field,
and suppose that  $\backslash(\mathfrak{m})$  is finitely generated over  $\backslash(A)$ . Then  $\backslash(A)$  is Noetherian.
-/
theorem isNoetherianRing_of_isLocalRing_of_field_inj_of_adicComplete_of_maximalIdeal_finite
  (R : Type) [CommRing R] [IsLocalRing R] [IsAdicComplete (IsLocalRing.maximalIdeal R) R]
  (k : Type) [Field k] [Algebra k R] [NoZeroSMulDivisors k R]
  (hfg : (IsLocalRing.maximalIdeal R).FG) : IsNoetherianRing R := by
  sorry
end Problem50

```

Exercise (51). A Noetherian topological ring in which the topology is defined by an ideal contained in the Jacobson radical is called a Zariski ring. Let A be a Noetherian ring, \mathfrak{a} an ideal of A , and \hat{A} the \mathfrak{a} -adic completion of A . Prove that \hat{A} is faithfully flat over A if and only if A is a Zariski ring for the \mathfrak{a} -topology.

```

import Mathlib

namespace Problem51

/--
A Noetherian topological ring in which the topology is defined by an ideal contained in the
Jacobson radical is called a \textit{Zariski ring}.
Let  $(A, \mathfrak{a})$  be a Noetherian ring,  $\mathfrak{a}$  an ideal of  $A$ , and  $\widehat{A}$  the  $\mathfrak{a}$ -adic completion of  $A$ .
Prove that  $\widehat{A}$  is faithfully flat over  $A$  if and only if  $A$  is a Zariski ring for the  $\mathfrak{a}$ -topology.
-/
theorem adicCompletion_faithfullyFlat_iff (A : Type) [CommRing A] [IsNoetherianRing A]
  (I : Ideal A) : Module.FaithfullyFlat A (AdicCompletion I A) ↔ I ≤ Ring.jacobson A := by
  sorry

end Problem51

```

Exercise (52). Let R be a ring, \mathfrak{m} is an ideal in the Jacobson radical of R , and $G_1, G_2 \in R[x]$ are polynomials such that G_1 is monic. If $G_i \bmod \mathfrak{m}$ generate the unit ideal of $R/\mathfrak{m}[x]$, then G_1, G_2 together generate the unit ideal of $R[x]$.

```

import Mathlib

namespace Problem52

/--
Let  $R$  be a ring,  $\mathfrak{m}$  is an ideal in the Jacobson radical of  $R$ ,
and  $G_1, G_2 \in R[x]$  are polynomials such that  $G_1$  is monic.
If  $G_i \bmod \mathfrak{m}$  generate the unit ideal of  $R/\mathfrak{m}[x]$ ,
then  $G_1, G_2$  together generate the unit ideal of  $R[x]$ .
-/
theorem generate_unit_ideal_of_quotient (R : Type) [CommRing R] (m : Ideal R)
  (h_le_jac : m ≤ Ring.jacobson R) (G1 G2 : Polynomial R) (h_monic : G1.Monic)
  (h_gen : Ideal.span {G1.map (Ideal.Quotient.mk m), G2.map (Ideal.Quotient.mk m)} = ⊤) :
  Ideal.span {G1, G2} = ⊤ := by
  sorry

end Problem52

```

Exercise (53). Let k be a field, and set $A = k[X, Y, Z]/(X^2 - Y^2, Y^2 - Z^2, XY, YZ, ZX)$. Show that A is Gorenstein.

```

import Mathlib

namespace Problem53

open IsLocalRing ModuleCat CategoryTheory MvPolynomial

```

```

instance (R : Type) [CommRing R] : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives.{0} (ModuleCat.{0} R)

/--
A Noetherian local ring  $R$  is a Gorenstein ring if  $\mathrm{inj}.\dim_R R < +\infty$ .
-/
class IsGorensteinLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  injDim_le_infty :
     $\exists n : \mathbb{N}, \forall i : \mathbb{N}, n \leq i \rightarrow$ 
    Subsingleton (Abelian.Ext.{0} (of.{0} R (ResidueField R)) (of.{0} R R) i)

/--
A Noetherian ring is a Gorenstein ring if its localization at every maximal ideal is a
Gorenstein local ring.
-/
class IsGorensteinRing (R : Type) [CommRing R] : Prop extends IsNoetherianRing R where
  localization_maximal_isGorensteinLocalRing :
     $\forall m : \text{Ideal } R, (m : \text{m.IsMaximal}) \rightarrow \text{IsGorensteinLocalRing } (\text{Localization.AtPrime } m)$ 

/--
Let  $(k)$  be a field, and set  $A = k[X, Y, Z]/(X^2 - Y^2, Y^2 - Z^2, XY, YZ, ZX)$ .
Show that  $A$  is Gorenstein.
-/
theorem isGorensteinRing_quot_x2_sub_y2_y2_sub_z2_xy_yz_zx (k : Type) [Field k] :
  IsGorensteinRing <| MvPolynomial (Fin 3) k / Ideal.span ({(X 0)^2 - (X 1)^2, (X 1)^2 - (X 2)^2,
    (X 0) * (X 1), (X 1) * (X 2), (X 2) * (X 0)} : Set (MvPolynomial (Fin 3) k)) := by
  sorry

end Problem53

```

Exercise (54). Let A be a \mathbb{Q} -algebra. Suppose that $x \in A$ and $D \in \text{Der}(A)$ are such that $Dx = 1$ and $\bigcap_{n=1}^{\infty} x^n A = (0)$. Show that x is a non-zero-divisor of A .

```

import Mathlib

namespace Problem54

/--
Let  $(A)$  be a  $\mathbb{Q}$ -algebra.
Suppose that  $(x \in A)$  and  $(D \in \text{Der}(A))$  are such that  $(Dx = 1)$  and
 $(\bigcap_{n=1}^{\infty} x^n A = (0))$ .
Show that  $(x)$  is a non-zero-divisor of  $(A)$ .
-/
theorem not_zero_divisor_of_hausdorff_of_der_eq_one (A : Type) [CommRing A] [Algebra  $\mathbb{Q}$  A]
  (x : A) (D : Derivation  $\mathbb{Z}$  A A) (h_dx : D x = 1) (h_hausdorff : IsHausdorff (Ideal.span {x} A)) :
  x  $\in$  nonZeroDivisors A := by
  sorry

end Problem54

```

Exercise (55). A module M over a ring R is stably free if there exists a free finitely generated module F over R such that

$$M \oplus F$$

is a free module. Prove that if M is stably free and not finitely generated then M is free.

```
import Mathlib

namespace Problem55

/--
A module  $M$  over a ring  $R$  is stably free if there exists a free finitely
generated module  $F$  over  $R$  such that
 $M \oplus F$ 
is a free module.
-/
def IsStablyFree (R : Type) (M : Type) [CommRing R] [AddCommGroup M] [Module R M] : Prop :=
  ∃ (N : Type) (N : AddCommGroup N) (N : Module R N),
    Module.Finite R N ∧ Module.Free R N ∧ Module.Free R (M × N)

/--
Prove that if  $M$  is stably free and not finitely generated then  $M$  is free.
-/
theorem stablyFree_iff_free_of_not_fg (R : Type) (M : Type) [CommRing R] [AddCommGroup M]
  [Module R M] (h : ¬ Module.Finite R M) : Module.Free R M ↔ IsStablyFree R M := by
  sorry

end Problem55
```

Exercise (56). Let $R \rightarrow S$ be a faithfully flat ring map. Let M be an R -module. If the S -module $S \otimes_R M$ is projective, then M is projective.

```
import Mathlib

namespace Problem56

/--
Let  $R \rightarrow S$  be a faithfully flat ring map. Let  $M$  be an  $R$ -module.
If the  $S$ -module  $S \otimes_R M$  is projective, then  $M$  is projective.
-/
theorem projective_of_faithfullyFlat_base_change (R S M : Type) [CommRing R] [CommRing S]
  [Algebra R S] [Module.FaithfullyFlat R S] [AddCommGroup M] [Module R M]
  [Module.Projective S (TensorProduct R S M)] : Module.Projective R M := by
  sorry

end Problem56
```

Exercise (57). Let A be a domain and K its field of fractions. $x \in K$ is called *almost integral* if there exists an element $r \in A, r \neq 0$ such that $rx^n \in A$ for all $n \geq 0$. A is called *completely integrally closed* if every almost integral element of K is contained in A . Show that if A is completely integrally closed, so is $A[X]$.

```
import Mathlib

namespace Problem57

/--
Let  $(A)$  be a domain and  $(K)$  its field of fractions.
 $(x \in K)$  is called almost integral if there exists an element  $(r \in A, r \neq 0)$ 
such that  $(rx^n \in A)$  for all  $(n \geq 0)$ .
-/
def IsAlmostIntegral {A : Type} [CommRing A] [IsDomain A] (x : FractionRing A) : Prop :=
   $\exists r : A, r \neq 0 \wedge \forall n : \mathbb{N}, \exists y : A, r \cdot (x ^ n) = \text{algebraMap } A (\text{FractionRing } A) y$ 

/--
 $(A)$  is called completely integrally closed if every almost integral element
of  $(K)$  is contained in  $(A)$ .
-/
def IsCompletelyIntegrallyClosed (A : Type) [CommRing A] [IsDomain A] : Prop :=
   $\forall x : \text{FractionRing } A, \text{IsAlmostIntegral } x \rightarrow \exists y : A, x = \text{algebraMap } A (\text{FractionRing } A) y$ 

/--
Let  $(A)$  be a domain. Show that if  $(A)$  is completely integrally closed, so is  $(A[X])$ .
-/
theorem completely_integrally_closed_polynomial_ring {A : Type} [CommRing A] [IsDomain A]
  (h : IsCompletelyIntegrallyClosed A) : IsCompletelyIntegrallyClosed (Polynomial A) := by
  sorry

end Problem57
```

Exercise (58). Suppose that (R, \mathfrak{P}) is a local Noetherian ring, and let (S, \mathfrak{Q}) be a local Noetherian R -algebra such that $\mathfrak{P}S \subseteq \mathfrak{Q}$. If M is a finitely generated S -module, show that M is flat as an R -module if $M/\mathfrak{P}^n M$ is flat as an R/\mathfrak{P}^n -module for every n .

```
import Mathlib

namespace Problem58

open TensorProduct

/--
Suppose that  $(R, \mathfrak{P})$  is a local Noetherian ring,
and let  $(S, \mathfrak{Q})$  be a local Noetherian  $R$ -algebra such that
 $\mathfrak{P}S \subseteq \mathfrak{Q}$ .
If  $M$  is a finitely generated  $S$ -module, show that  $M$  is flat as an  $R$ -module
if  $M / \mathfrak{P}^n M$  is flat as an  $R / \mathfrak{P}^n$ -module for every  $n$ .
```

```

-/
theorem flat_of_flat_over_quotient (R S : Type) [CommRing R] [CommRing S]
  [IsLocalRing R] [IsLocalRing S] [IsNoetherianRing R] [IsNoetherianRing S] [Algebra R S]
  (h_map : Ideal.map (algebraMap R S) (IsLocalRing.maximalIdeal R) ≤ IsLocalRing.maximalIdeal S)
  (M : Type) [AddCommGroup M] [Module S M] [Module R M] [IsScalarTower R S M] [Module.Finite S M]
  (h_flat_quotient : ∀ (n : ℕ), Module.Flat (R / (IsLocalRing.maximalIdeal R) ^ n) ((R /
    (IsLocalRing.maximalIdeal R) ^ n) ⊗[R] M)) :
  Module.Flat R M := by
  sorry

end Problem58

```

Exercise (59). Let k be a field, X and Y indeterminates, and suppose that α is a positive irrational number. Show the map $v : k[X, Y] \rightarrow \mathbb{R} \cup \{\infty\}$ defined by

$$v\left(\sum c_{n,m} X^n Y^m\right) = \min\{n + m\alpha \mid c_{n,m} \neq 0\}$$

determines a valuation of $k(X, Y)$ with value group $\mathbb{Z} + \mathbb{Z}\alpha$.

```

import Mathlib

namespace Problem59

/--
Let  $(k)$  be a field,  $(X)$  and  $(Y)$  indeterminates, and suppose that  $(\alpha)$  is a
positive irrational number. Show the map  $(v : k[X, Y] \rightarrow \mathbb{R} \cup \{\infty\})$ 
defined by

$$v\left(\sum c_{n,m} X^n Y^m\right) = \min\{n + m\alpha \mid c_{n,m} \neq 0\}$$

determines a valuation of  $(k(X, Y))$  with value group  $(\mathbb{Z} + \mathbb{Z}\alpha)$ .
-/
theorem exists_unique_valuation_eq ( $\alpha : \mathbb{R}$ ) (h_pos :  $\alpha > 0$ ) (h_irr : Irrational  $\alpha$ )
  ( $k : Type$ ) [Field  $k$ ] :  $\exists!$  ( $v : \text{AddValuation} (\text{FractionRing} (\text{MvPolynomial} (\text{Fin } 2) k)) (\text{WithTop } \mathbb{R}))$ ,
   $\forall$  ( $f : \text{MvPolynomial} (\text{Fin } 2) k$ ),  $v$  (algebraMap  $\_ \_ f$ ) = Finset.inf (Finset.image ( $\text{fun } s \mapsto ((s \cdot 0 +$ 
     $\alpha \cdot s \cdot 1) : \text{WithTop } \mathbb{R})) f.\text{support}) \text{ id} := by
  sorry

end Problem59$ 
```

Exercise (60). Let R be a Noetherian domain, and suppose that for every maximal ideal P of R the ring R_P is factorial. Let $I \subset R$ be an ideal. Prove that I is an invertible module iff I has pure codimension 1. (We say that an ideal I in a ring R has pure codimension 1 if every associated prime ideal of I has codimension 1. We include the case when I has no associated primes at all—that is, when $I = R$.)

```

import Mathlib

namespace Problem60

open Problem60

/--
For a Noetherian domain  $(R, \cdot)$ , we say that an ideal  $I \subset R$  is invertible if
it is not the zero ideal and there exists an ideal  $N \subset R$  such that  $N \cdot I$  is principal
and  $N$  is not the zero ideal.
-/
def Ideal.Invertible {R : Type} [CommRing R] [IsDomain R] (I : Ideal R) : Prop :=
  I ≠ 0 ∧ ∃ (N : Ideal R), (N * I).IsPrincipal ∧ N ≠ 0

/--
Let  $R$  be a Noetherian domain, and suppose that for every maximal ideal  $\mathfrak{p}$  of  $R$  the ring  $R_{\mathfrak{p}}$ 
is factorial. Let  $I \subset R$  be an ideal. Prove that  $I$  is an invertible module iff
 $I$  has pure codimension 1. (We say that an ideal  $I$  in a ring  $R$  has pure codimension 1 if
every associated prime ideal of  $I$  has codimension 1. We include the case when  $I$  has no
associated primes at all---that is, when  $I = R$ .)
-/
theorem invertible_iff_codimension_one (R : Type) [CommRing R] [IsDomain R] [IsNoetherianRing R]
  (h_ufd : ∀ (p : Ideal R), (h : p.IsMaximal) → UniqueFactorizationMonoid (Localization.AtPrime p))
  (I : Ideal R) : I.Invertible ↔ ∀ (p : associatedPrimes R I), ringKrullDim (R / p.1) = 1 := by
  sorry

end Problem60

```

Exercise (61). Let $R \rightarrow S$ be a ring map. Let $I \subset R$ be an ideal. Assume

1. $I^2 = 0$,
2. $R \rightarrow S$ is flat, and
3. $R/I \rightarrow S/IS$ is formally smooth.

Show $R \rightarrow S$ is formally smooth.

```

import Mathlib

namespace Problem61

/--
Let  $(R \rightarrow S)$  be a ring map. Let  $I \subset R$  be an ideal. Assume
\begin{enumerate}
  \item  $I^2 = 0$ ,
  \item  $R \rightarrow S$  is flat, and
  \item  $R/I \rightarrow S/IS$  is formally smooth.
\end{enumerate}
Show  $R \rightarrow S$  is formally smooth.

```

```

-/
theorem formallySmooth_of_formallySmooth_quotient (R S : Type) [CommRing R] [CommRing S]
  [Algebra R S] [Module.Flat R S] (I : Ideal R) (h : I ^ 2 = 0)
  [Algebra.FormallySmooth (R / I) (S / (I.map (algebraMap R S)))] :
  Algebra.FormallySmooth R S := by
  sorry
end Problem61

```

Exercise (62). Let $\varphi : R \rightarrow S$ be a smooth ring map. Let $\sigma : S \rightarrow R$ be a left inverse to φ . Set $I = \text{Ker}(\sigma)$. If I/I^2 is free, show $S^\wedge \cong R[[t_1, \dots, t_d]]$ as R -algebras, where S^\wedge is the I -adic completion of S .

```

import Mathlib

namespace Problem62

/--
Let  $\varphi : R \rightarrow S$  be a smooth ring map. Let  $\sigma : S \rightarrow R$  be a left inverse
to  $\varphi$ . Set  $I = \text{Ker}(\sigma)$ . If  $I/I^2$  is free,
show  $S^\wedge \cong R[[t_1, \dots, t_d]]$  as  $R$ -algebras,
where  $S^\wedge$  is the  $I$ -adic completion of  $S$ .
-/
theorem adicCompletion_equiv_of_smooth (R S : Type) [CommRing R] [CommRing S]
  [Algebra R S] [Algebra.Smooth R S] ( $\sigma : S \rightarrow R$ )
  (h : Function.LeftInverse  $\sigma$  (algebraMap R S)) (hf : Module.Free R  $\sigma$ .ker.Cotangent) :
   $\exists d : \mathbb{N}$ , Nonempty (AdicCompletion (RingHom.ker  $\sigma$ ) S  $\simeq_a[R]$  MvPowerSeries (Fin d) R) := by
  sorry
end Problem62

```

Exercise (63). Let $R \rightarrow S$ be a formally unramified ring map. Show there exists a surjection of R -algebras $S' \rightarrow S$ whose kernel is an ideal of square zero with the following universal property: Given any commutative diagram

$$\begin{array}{ccc}
 S & \xrightarrow{a} & A/I \\
 \uparrow & & \uparrow \\
 R & \xrightarrow{b} & A
 \end{array}$$

where $I \subset A$ is an ideal of square zero, there is a unique R -algebra map $\alpha' : S' \rightarrow A$ such that $S' \rightarrow A \rightarrow A/I$ is equal to $S' \rightarrow S \rightarrow A/I$.

```

import Mathlib

namespace Problem63

/--

```

```

The universal property:
Given any commutative diagram
\[\begin{tikzcd}
S \arrow[r, "a"] & A/I \\
R \arrow[u] \arrow[r, "b"] & A \arrow[u]
\end{tikzcd}\]
\]
where  $(I \subset A)$  is an ideal of square zero, there is a unique  $(R \setminus)$ -algebra map
 $(\alpha': S' \rightarrow A/I)$  such that  $(S' \rightarrow A \rightarrow A/I)$  is equal to  $(S' \rightarrow S \rightarrow A/I)$ .
-/
def UniversalProperty.liftOfSqZeroIdeal {R S S' : Type} [CommRing R] [CommRing S] [CommRing S']
  [Algebra R S] [Algebra R S'] (f : S' →a[R] S) :=
  ∀ (A : Type) [CommRing A] [Algebra R A] (I : Ideal A) (g : S →a[R] /AI),
  I^2 = 0 → (g.toRingHom.comp (algebraMap R S) = (Ideal.Quotient.mk I).comp (algebraMap R A)) →
  ∃! (g' : S' →a[R] A), (Ideal.Quotient.mk I).comp g'.toRingHom = g.comp f

/--
Let  $(R \rightarrow S)$  be a formally unramified ring map. Show there exists a surjection of
 $(R \setminus)$ -algebras  $(S' \rightarrow S)$  whose kernel is an ideal of square zero with the following
universal property:
Given any commutative diagram
\[\begin{tikzcd}
S \arrow[r, "a"] & A/I \\
R \arrow[u] \arrow[r, "b"] & A \arrow[u]
\end{tikzcd}\]
\]
where  $(I \subset A)$  is an ideal of square zero, there is a unique  $(R \setminus)$ -algebra map
 $(\alpha': S' \rightarrow A/I)$  such that  $(S' \rightarrow A \rightarrow A/I)$  is equal to  $(S' \rightarrow S \rightarrow A/I)$ .
-/
theorem surjection_of_formally_unramified (R S : Type) [CommRing R] [CommRing S]
  [Algebra R S] [Algebra.FformallyUnramified R S] :
  ∃ (S' : Type) (α : CommRing S') (α : Algebra R S') (f : S' →a[R] S), (RingHom.ker f) ^ 2 = 0 ∧
  UniversalProperty.liftOfSqZeroIdeal f := by
  sorry
end Problem63

```

Exercise (64). *Prove that the homogeneous coordinate ring of a smooth rational quartic in three-space*

$$R = k[s^4, s^3t, st^3, t^4] \subset k[s, t]$$

is not Cohen-Macaulay.

```

import Mathlib

namespace Problem64

section

```

```

open CategoryTheory Abelian Problem64

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) : ℕ∞ :=
  sSup {n : ℕ∞ | ∀ i : ℕ, i < n → Subsingleton (CategoryTheory.Abelian.Ext.{0} N M i)}

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) : ℕ∞ :=
  moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) : ℕ∞ :=
  (IsLocalRing.maximalIdeal R).depth M

variable (R)

class IsCohenMacaulayLocalRing : Prop extends IsLocalRing R where
  depth_eq_dim : ringKrullDim R = IsLocalRing.depth (ModuleCat.of R R)

class IsCohenMacaulayRing : Prop where
  CM_localize : ∀ p : Ideal R, ∀ (_ : p.IsPrime), IsCohenMacaulayLocalRing (Localization.AtPrime p)

end

open MvPolynomial

/--
Prove that the homogeneous coordinate ring of a smooth rational quartic in three-space
\[
R=k[s^4, s^3t, st^3, t^4] \subset k[s,t]
\]
is not Cohen-Macaulay.
-/
theorem homogeneous_coordinate_ring_not_isCohenMacaulayRing (k : Type) [Field k] :
  ¬ IsCohenMacaulayRing (Algebra.adjoin k ({(X 0) ^ 4, (X 0) ^ 3 * X 1,
    X 0 * (X 1) ^ 3, (X 1) ^ 4} : Set (MvPolynomial (Fin 2) k))) := by
  sorry

end Problem64

```

Exercise (65). *If A is a Noetherian Gorenstein ring, then so is the polynomial ring $A[X]$.*

```

import Mathlib

namespace Problem65

open IsLocalRing ModuleCat CategoryTheory Polynomial

instance (R : Type) [CommRing R] : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives.{0} (ModuleCat.{0} R)

```

```

/--
A Noetherian local ring  $R$  is a Gorenstein ring if  $\dim_{\mathrm{inj}} R < +\infty$ .
-/
class IsGorensteinLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  injDim_le_infinity :
     $\exists n : \mathbb{N}, \forall i : \mathbb{N}, n \leq i \rightarrow$ 
    Subsingleton (Abelian.Ext.{0} (of.{0} R (ResidueField R)) (of.{0} R R) i)

/--
A Noetherian ring is a Gorenstein ring if its localization at every maximal ideal is a
Gorenstein local ring.
-/
class IsGorensteinRing (R : Type) [CommRing R] : Prop extends IsNoetherianRing R where
  localization_maximal_isGorensteinLocalRing :
     $\forall m : \text{Ideal } R, (m : \text{Ideal } R) \rightarrow \text{IsGorensteinLocalRing } (\text{Localization.AtPrime } m)$ 

/--
If  $(A)$  is a Noetherian Gorenstein ring, then so is the polynomial ring  $(A[X])$ .
-/
theorem Polynomial.isGorensteinRing {R : Type} [CommRing R] [IsGorensteinRing R] :
  IsGorensteinRing  $R[X]$  := by
  sorry

end Problem65

```

Exercise (66). Show that if an ideal I in a Noetherian ring R can be generated by a regular sequence, then it can be generated by a set of elements that is a regular sequence in any order.

```

import Mathlib

namespace Problem66

open RingTheory

/--
Show that if an ideal  $I$  in a Noetherian ring  $R$  can be generated by a regular sequence,
then it can be generated by a set of elements that is a regular sequence in any order.
-/
theorem exists_eq_ofList_and_isRegular_of_perm {R : Type} [CommRing R] [IsNoetherianRing R] (I :
  Ideal R) (rs : List R)
  (gen : I = Ideal.ofList rs) (h2 : Sequence.IsRegular R rs) :  $\exists rs' : \text{List } R,$ 
   $I = \text{Ideal.ofList } rs' \wedge (\forall l : \text{List } R, (l.\text{Perm } rs') \rightarrow \text{Sequence.IsRegular } R l)$  := by
  sorry

end Problem66

```

Exercise (67). Let A be the ring $k[[x_1, \dots, x_n]]$, where k is a field, $n \in \mathbb{N}$, $n \neq 0$. Show that there is **no** isomorphism

$$A \otimes_k A \cong k[[x_1, \dots, x_n, y_1, \dots, y_n]].$$

```

import Mathlib

namespace Problem67

open scoped TensorProduct

/--
Let  $A$  be the ring  $k[[x_1, \dots, x_n]]$ , where  $k$  is a field,  $n \in \mathbb{N}$ ,  $n \neq 0$ .
Show that there is  $\text{no}$  isomorphism

$$A \cong_k A \otimes_k k[[x_1, \dots, x_n, y_1, \dots, y_n]].$$

-/
theorem isEmpty_mvPowerSeries_tensor_mvPowerSeries_algEquiv
  {k : Type} [Field k] (n : ℕ) (hn : n ≠ 0) :
  IsEmpty ((MvPowerSeries (Fin n) k)  $\otimes$ [k] (MvPowerSeries (Fin n) k)  $\simeq_a$  [k]
    (MvPowerSeries (Fin (n + n)) k)) := by
  sorry

end Problem67

```

Exercise (68). Let A be a Noetherian local ring with maximal ideal \mathfrak{m} . For any $f \in \mathfrak{m}$ such that f is not nilpotent, A_f is Jacobson.

```

import Mathlib

namespace Problem68

/--
Let  $A$  be a Noetherian local ring with maximal ideal  $\mathfrak{m}$ .
For any  $f \in \mathfrak{m}$  such that  $f$  is not nilpotent,  $A_f$  is Jacobson.
-/
theorem localization_jacobson_of_one_lt_ringKrullDim (R : Type) [CommRing R] [IsLocalRing R]
  [IsNoetherianRing R] (f : R) (hf : f ∈ IsLocalRing.maximalIdeal R) (ne0 : ¬ IsNilpotent f) :
  IsJacobsonRing (Localization.Away f) := by
  sorry

end Problem68

```

Exercise (69). If R is a regular local ring with maximal ideal \mathfrak{m} and $P \in \text{Spec}(R[x])$ is a prime ideal with $\mathfrak{m} = P \cap R$, then $R[x]_P$ is regular.

```

import Mathlib

namespace Problem69

open IsLocalRing Polynomial

/--

```

```

A commutative local noetherian ring  $R$  is regular if  $\dim m/m^2 = \dim R$ .
-/
class IsRegularLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  reg : Module.finrank (ResidueField R) (CotangentSpace R) = ringKrullDim R

/--
Let  $(A)$  be a Noetherian ring.
If  $(R)$  is a regular local ring with maximal ideal  $(\mathfrak{m})$  and
 $(P \in \operatorname{Spec}(R[x]))$  is a prime ideal with  $\mathfrak{m} = P \cap R$ ,
then  $(R[x]_P)$  is regular.
-/
theorem IsRegularLocalRing.regularAtPrime {R : Type} [CommRing R] [IsRegularLocalRing R]
  (P : Ideal R[X]) [P.IsPrime] [P.LiesOver (maximalIdeal R)] :
  IsRegularLocalRing (Localization.AtPrime P) := by
  sorry

end Problem69

```

Exercise (70). All rings considered are noetherian. Show that if R is an integral domain contained in the local ring (S, Q) , then there is a minimal prime of S contracting to 0 in R .

```

import Mathlib

namespace Problem70

/--
All rings considered are noetherian.
Show that if  $(R)$  is an integral domain contained in the local ring  $(S, Q)$ ,
then there is a minimal prime of  $(S)$  contracting to  $(0)$  in  $(R)$ .
-/
theorem exists_minimalPrime_map_zero (R S : Type) [CommRing R] [IsDomain R] [IsNoetherianRing R]
  [CommRing S] [IsNoetherianRing S] [IsLocalRing S] [Algebra R S] [NoZeroSMulDivisors R S] :
   $\exists (p : \text{minimalPrimes } S), \text{Ideal.comap } (\text{algebraMap } R S) p.1 = \mathfrak{0} := by
  sorry

end Problem70$ 
```

Exercise (71). Let G be a finite group acting as automorphisms of an algebra R over a field of characteristic 0 . Show that if R is Cohen-Macaulay, then the ring of invariants R^G is Cohen-Macaulay.

```

import Mathlib

namespace Problem71

section

variable (A B : Type) [CommRing A] [CommRing B] [Algebra A B]

```

```

variable (G : Type) [Monoid G] [MulSemiringAction G B] [SMulCommClass G A B]

/--
The set of fixed points under a group action, as a subring.
-/
def FixedPoints.subring : Subring B where
  -- := FixedPoints.addSubgroup G B
  -- := FixedPoints.submonoid G B

/--
The set of fixed points under a group action, as a subalgebra.
-/
def FixedPoints.subalgebra : Subalgebra A B where
  -- := FixedPoints.addSubgroup G B
  -- := FixedPoints.submonoid G B
  algebraMap_mem' r := by simp

end

section

open CategoryTheory Abelian Problem71

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) : ℕ :=
  sSup {n : ℕ | ∀ i : ℕ, i < n → Subsingleton (CategoryTheory.Abelian.Ext.{0} N M i)}

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) : ℕ :=
  moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) : ℕ :=
  (IsLocalRing.maximalIdeal R).depth M

variable (R)

class IsCohenMacaulayLocalRing : Prop extends IsLocalRing R where
  depth_eq_dim : ringKrullDim R = IsLocalRing.depth (ModuleCat.of R R)

class IsCohenMacaulayRing : Prop where
  CM_localize : ∀ p : Ideal R, ∀ (_ : p.IsPrime), IsCohenMacaulayLocalRing (Localization.AtPrime p)

end

/--
Let  $(G)$  be a finite group acting as automorphisms of an algebra  $(R)$  over a field of
characteristic  $(0)$ . Show that if  $(R)$  is Cohen-Macaulay, then the ring of invariants
 $(R^G)$  is Cohen-Macaulay.
-/
theorem fixedPoints_isCohenMacaulayRing {R : Type} [CommRing R] (k : Type) [Field k]

```

```

[CharZero k] [Algebra k R] [IsNoetherianRing R] [IsCohenMacaulayRing R]
(G : Subgroup (R  $\simeq_a$  [k] R)) [Finite G] :
IsCohenMacaulayRing (FixedPoints.subalgebra k R G) := by
sorry

end Problem71

```

Exercise (72). *Let R be a Noetherian ring. Let M be a Cohen-Macaulay module over R . Then $M \otimes_R R[x_1, \dots, x_n]$ is a Cohen-Macaulay module over $R[x_1, \dots, x_n]$.*

```

import Mathlib

namespace Problem72

/--
The krull dimension of module, defined as `krullDim` of its support.
-/
noncomputable def Module.supportDim (R : Type) [CommRing R] (M : Type) [AddCommGroup M]
[Module R M] : WithBot  $\mathbb{N}_\infty$  :=
Order.krullDim (Module.support R M)

section

open CategoryTheory Abelian Problem72

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) :  $\mathbb{N}_\infty$  :=
sSup {n :  $\mathbb{N}_\infty$  |  $\forall i : \mathbb{N}, i < n \rightarrow \text{Subsingleton } (\text{CategoryTheory.Abelian.Ext}\{0\} \text{ } N \text{ } M \text{ } i)$ }

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) :  $\mathbb{N}_\infty$  :=
moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) :  $\mathbb{N}_\infty$  :=
(IsLocalRing.maximalIdeal R).depth M

class ModuleCat.IsCohenMacaulay [IsLocalRing R] (M : ModuleCat.{0} R) : Prop where
depth_eq_dim : Subsingleton M  $\vee$  Module.supportDim R M = IsLocalRing.depth M

variable (R)

class Module.IsCohenMacaulay (M : Type) [AddCommGroup M] [Module R M] : Prop where
depth_eq_dim :  $\forall p : \text{Ideal } R, \forall (- : p.\text{IsPrime}), (\text{ModuleCat.of } (\text{Localization.AtPrime } p) (\text{LocalizedModule.AtPrime } p \text{ } M)).\text{IsCohenMacaulay}$ 

end

open TensorProduct

```

```

/--
Let  $(R)$  be a Noetherian ring. Let  $(M)$  be a Cohen-Macaulay module over  $(R)$ .
Then  $(M \otimes_R R[x_1, \dots, x_n])$  is a Cohen-Macaulay module over  $(R[x_1, \dots, x_n])$ .
-/
theorem isCohenMacaulay_extendScalars_over_mvPolynomial_of_isCohenMacaulay
  (R : Type) [CommRing R] (M : Type) [AddCommGroup M] [Module R M]
  [IsNoetherianRing R] [Module.IsCohenMacaulay R M] (n : ℕ) :
  Module.IsCohenMacaulay (MvPolynomial (Fin n) R) ((MvPolynomial (Fin n) R) Ⓢ[R] M) := by
  sorry

end Problem72

```

Exercise (73). If I is an homogeneous ideal of $k[x_0, \dots, x_n]$, $R = k[x_0, \dots, x_n]/I$, then R is Cohen-Macaulay if and only if R_P is Cohen-Macaulay, where $P = (x_0, \dots, x_n)$.

```

import Mathlib

namespace Problem73

section

open CategoryTheory Abelian Problem73

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) : ℕ∞ :=
  sSup {n : ℕ | ∀ i : ℕ, i < n → Subsingleton (CategoryTheory.Abelian.Ext.{0} N M i)}

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) : ℕ∞ :=
  moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) : ℕ∞ :=
  (IsLocalRing.maximalIdeal R).depth M

variable (R)

class IsCohenMacaulayLocalRing : Prop extends IsLocalRing R where
  depth_eq_dim : ringKrullDim R = IsLocalRing.depth (ModuleCat.of R R)

class IsCohenMacaulayRing : Prop where
  CM_localize : ∀ p : Ideal R, ∀ (_ : p.IsPrime), IsCohenMacaulayLocalRing (Localization.AtPrime p)

end

attribute [local instance] MvPolynomial.gradedAlgebra

/--
If  $I$  is an homogeneous ideal of  $k[x_0, \dots, x_n]$ ,  $(R = k[x_0, \dots, x_n]/I)$ ,
then  $(R)$  is Cohen-Macaulay if and only if  $(R_P)$  is Cohen-Macaulay, where

```

```

\ ( P = (x_0, \dots, x_n) \).
-/
theorem mvPolynomial_quotient_isCohenMacaulayRing_iff (k : Type) [Field k] (n : ℕ)
  (R : Type) [CommRing R] (f : (MvPolynomial (Fin n) k) →+* R) (surj : Function.Surjective f)
  (homo : (RingHom.ker f).IsHomogeneous (MvPolynomial.homogeneousSubmodule (Fin n) k))
  (le : RingHom.ker f ≤ RingHom.ker MvPolynomial.constantCoeff) :
  IsCohenMacaulayRing R ↔
  IsCohenMacaulayRing (Localization.AtPrime ((RingHom.ker MvPolynomial.constantCoeff).map f)
    (hp := Ideal.map_isPrime_of_surjective surj le (H := RingHom.ker_isPrime _))) := by
  sorry
end Problem73

```

Exercise (74). Let R be a regular local ring and let x_1, \dots, x_c be a regular sequence in R . Let $y \in R$, $y \notin (x_1, \dots, x_c)$, and set $J := ((x_1, \dots, x_c) : y)$. Prove that R/J is Gorenstein.

```

import Mathlib

namespace Problem74

open IsLocalRing ModuleCat CategoryTheory

instance (R : Type) [CommRing R] : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives.{0} (ModuleCat.{0} R)

/--
A commutative local noetherian ring  $R$  is regular if  $\dim m/m^2 = \dim R$ .
-/
class IsRegularLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  reg : Module.frank (ResidueField R) (CotangentSpace R) = ringKrullDim R

/--
A Noetherian local ring  $R$  is a Gorenstein ring if  $\mathrm{inj}.\dim_R R < +\infty$ .
-/
class IsGorensteinLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  injDim_le_infty :
    ∃ n : ℕ, ∀ i : ℕ, n ≤ i →
      Subsingleton (Abelian.Ext.{0} (of.{0} R (ResidueField R)) (of.{0} R R) i)

/--
A Noetherian ring is a Gorenstein ring if its localization at every maximal ideal is a
Gorenstein local ring.
-/
class IsGorensteinRing (R : Type) [CommRing R] : Prop extends IsNoetherianRing R where
  localization_maximal_isGorensteinLocalRing :
    ∀ m : Ideal R, (m.IsMaximal) → IsGorensteinLocalRing (Localization.AtPrime m)
variable {R : Type} [CommRing R]

/--
Let  $R$  be a regular local ring and let  $x_1, \dots, x_c$  be a regular sequence in  $R$ .

```

```

Let  $y \in R$ ,  $y \notin (x_1, \dots, x_c)$ , and set  $J := (x_1, \dots, x_c : y)$ . Prove that  $R/J$  is Gorenstein.
-/
theorem IsRegularLocalRing.gorensteinAtRegularSequence {R : Type} [CommRing R]
  [IsRegularLocalRing R] {rs : List R} (reg : RingTheory.Sequence.IsRegular R rs) (y : R)
  (h : y  $\notin$  Ideal.ofList rs) : IsGorensteinRing (R / (Ideal.ofList rs / Ideal.span {y})) := by
  sorry
end Problem74

```

Exercise (75). Let A be a graded Noetherian ring, with A_0 a field and A generated by A_1 . Show that A is Cohen-Macaulay if and only if for all homogeneously prime \mathfrak{p} , $(A_{\mathfrak{p}})_0$ is Cohen-Macaulay.

```

import Mathlib

namespace Problem75

open IsLocalRing ModuleCat CategoryTheory Problem75

section

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) :  $\mathbb{N}_{\infty}$  :=
  sSup {n :  $\mathbb{N}_{\infty}$  |  $\forall i : \mathbb{N}, i < n \rightarrow \text{Subsingleton } (\text{CategoryTheory.Abelian.Ext}\{0\} \text{ N M } i)$ }

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) :  $\mathbb{N}_{\infty}$  :=
  moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) :  $\mathbb{N}_{\infty}$  :=
  (IsLocalRing.maximalIdeal R).depth M

variable (R)

class IsCohenMacaulayLocalRing : Prop extends IsLocalRing R where
  depth_eq_dim : ringKrullDim R = IsLocalRing.depth (ModuleCat.of R R)

class IsCohenMacaulayRing : Prop where
  CM_localize :  $\forall \mathfrak{p} : \text{Ideal } R, \forall (\_ : \mathfrak{p}.\text{IsPrime}), \text{IsCohenMacaulayLocalRing } (\text{Localization.AtPrime } \mathfrak{p})$ 

end

/--
Let  $A$  be a graded Noetherian ring, with  $A_0$  a field and  $A$  generated by  $A_1$ .
Show that  $A$  is Cohen-Macaulay if and only if for all homogeneously prime  $\mathfrak{p}$ ,
 $(A_{\mathfrak{p}})_0$  is Cohen-Macaulay.
-/
theorem gradedAlgebra_isCohenMacaulay_iff_homogeneously_localize {A : Type} [CommRing A]
  [IsNoetherianRing A]

```

```

    (R : ℕ → Submodule ℤ A) [GradedAlgebra R] (h : IsField (R 0)) (h1 : Algebra.adjoin (R 0) (R
    1) = (τ : Subalgebra (R 0) A)) : IsCohenMacaulayRing A ↔
    ∀ p : Ideal A, (p : p.IsPrime) → p.IsHomogeneous R →
    IsCohenMacaulayLocalRing (HomogeneousLocalization.AtPrime R p) := by
    sorry
end Problem75

```

Exercise (76). Let A be a Noetherian UFD of dimension $d \leq 3$. Prove that A is catenary.

```

import Mathlib

namespace Problem76

open List

/--
A ring  $R$  is said to be catenary if for any pair of prime ideals  $\mathfrak{p} \subset \mathfrak{q}$ , there exists an integer bounding the lengths of all finite chains of prime ideals
 $\mathfrak{p} = \mathfrak{p}_0 \subset \mathfrak{p}_1 \subset \dots \subset \mathfrak{p}_e = \mathfrak{q}$  and all maximal such chains have the same length.
-/
def IsCatenary (R : Type) [CommRing R] : Prop :=
  ∀ p q : PrimeSpectrum R, p ≤ q →
  ∃ n : ℕ, ∀ (l : LTSeries (PrimeSpectrum R)), l.head = p → l.last = q →
  (∀ l' : LTSeries (PrimeSpectrum R), l'.head = p → l'.last = q → l.toList <+ l'.toList → l' = l) →
  l.toList.length = n

/--
Let  $A$  be a Noetherian UFD of dimension  $d \leq 3$ . Prove that  $A$  is catenary.
-/
theorem IsCatenary.of_noetherian_ufd_of_dim_le_three {A : Type} [CommRing A] [IsNoetherianRing A]
  [IsDomain A] [UniqueFactorizationMonoid A] (h : ringKullDim A ≤ 3) : IsCatenary A := by
  sorry
end Problem76

```

Exercise (77). Let A be a Noetherian ring, $P \subset Q$ prime ideals such that $\text{ht } P = h$, $\text{ht } Q/P = d$, where $d > 1$. Prove that there exist infinitely many intermediate primes P' , $P \subset P' \subset Q$ such that $\text{ht } P' = h + 1$ and $\text{ht } Q/P' = d - 1$.

```

import Mathlib

namespace Problem77

/--
Let  $A$  be a Noetherian ring,  $P \subset Q$  prime ideals such that
 $\text{ht } P = h$ ,  $\text{ht } Q/P = d$ , where  $d > 1$ .
Prove that there exist infinitely many intermediate primes  $P'$ ,  $P \subset P' \subset Q$ 

```

```

such that  $\text{ht } P' = h + 1$  and  $\text{ht } Q/P' = d - 1$ .
-/
theorem infinite_intermediate_primes (R : Type) [CommRing R] [IsNoetherianRing R] (P Q : Ideal R)
  (le : P ≤ Q) [P.IsPrime] [Q.IsPrime] (h d : ℕ) (lt : 1 < d) (ht1 : P.height = h)
  (ht2 : (Q.map (Ideal.Quotient.mk P)).height = d) :
  {P' : Ideal R | P ≤ P' ∧ P' ≤ Q ∧ P'.IsPrime ∧ P'.height = h + 1 ∧
    (Q.map (Ideal.Quotient.mk P')).height = d - 1}.Infinite := by
  sorry

end Problem77

```

Exercise (78). *Let A be a local Cohen–Macaulay (CM) ring that is a quotient of a regular local ring. If A is a UFD, then A is Gorenstein.*

```

import Mathlib

namespace Problem78

open IsLocalRing ModuleCat CategoryTheory Problem78

section

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) : ℕ∞ :=
  sSup {n : ℕ∞ | ∀ i : ℕ, i < n → Subsingleton (CategoryTheory.Abelian.Ext.{0} N M i)}

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) : ℕ∞ :=
  moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) : ℕ∞ :=
  (IsLocalRing.maximalIdeal R).depth M

variable (R)

class IsCohenMacaulayLocalRing : Prop extends IsLocalRing R where
  depth_eq_dim : ringKrullDim R = IsLocalRing.depth (ModuleCat.of R R)

class IsCohenMacaulayRing : Prop where
  CM_localize : ∀ p : Ideal R, ∀ (_ : p.IsPrime), IsCohenMacaulayLocalRing (Localization.AtPrime p)

end

/--
A commutative local noetherian ring  $R$  is regular if  $\dim m/m^2 = \dim R$ .
-/
class IsRegularLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  reg : Module.finnrank (ResidueField R) (CotangentSpace R) = ringKrullDim R

```

```

/--
A Noetherian local ring  $R$  is a Gorenstein ring if  $\dim_{\mathcal{M}} R < +\infty$ .
-/
class IsGorensteinLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  injDim_le_infty :
     $\exists n : \mathbb{N}, \forall i : \mathbb{N}, n \leq i \rightarrow$ 
    Subsingleton (Abelian.Ext.{0} (of.{0} R (ResidueField R)) (of.{0} R R) i)

/--
A Noetherian ring is a Gorenstein ring if its localization at every maximal ideal is a
Gorenstein local ring.
-/
class IsGorensteinRing (R : Type) [CommRing R] : Prop extends IsNoetherianRing R where
  localization_maximal_isGorensteinLocalRing :
     $\forall m : \text{Ideal } R, (- : m.\text{IsMaximal}) \rightarrow \text{IsGorensteinLocalRing } (\text{Localization.AtPrime } m)$ 

/--
Let  $A$  be a local Cohen-Macaulay (CM) ring that is a quotient of a regular local ring.
If  $A$  is a UFD, then  $A$  is Gorenstein.
-/
theorem IsCohenMacaulayLocalRing.isGorensteinRing_of_ufd {A B : Type} [CommRing A]
  [IsCohenMacaulayLocalRing A] [IsDomain A] [UniqueFactorizationMonoid A] [CommRing B]
  [IsRegularLocalRing B] {f : B  $\twoheadrightarrow$  A} (hf : Function.Surjective f) :
  IsGorensteinRing A := by
  sorry

end Problem78

```

Exercise (79). Let B be a regular local ring and $I \subset B$ an ideal such that B/I is Gorenstein but not a complete intersection. Show that I cannot have height 0 or 1.

```

import Mathlib

namespace Problem79

open IsLocalRing ModuleCat CategoryTheory

instance (R : Type) [CommRing R] : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives.{0} (ModuleCat.{0} R)

/--
A commutative local noetherian ring  $R$  is regular if  $\dim \mathfrak{m}/\mathfrak{m}^2 = \dim R$ .
-/
class IsRegularLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  reg : Module.finrank (ResidueField R) (CotangentSpace R) = ringKrullDim R

/--
A Noetherian local ring  $R$  is a Gorenstein ring if  $\dim_{\mathcal{M}} R < +\infty$ .
-/

```

```

class IsGorensteinLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  injDim_le_infty :
    ∃ n : ℕ, ∀ i : ℕ, n ≤ i →
      Subsingleton (Abelian.Ext.{0} (of.{0} R (ResidueField R)) (of.{0} R R) i)

/--
A Noetherian ring is a Gorenstein ring if its localization at every maximal ideal is a
Gorenstein local ring.
-/
class IsGorensteinRing (R : Type) [CommRing R] : Prop extends IsNoetherianRing R where
  localization_maximal_isGorensteinLocalRing :
    ∀ m : Ideal R, (m.IsMaximal) → IsGorensteinLocalRing (Localization.AtPrime m)

/--
A Noetherian local ring  $R$  is a local complete intersection if every surjection of local rings
 $R \twoheadrightarrow \widehat{A}$  with  $R$  a regular local ring, the kernel of  $R \twoheadrightarrow \widehat{A}$  is generated by a
regular sequence.
-/
@[stacks 09Q3]
class IsLocalCompleteIntersectionRing (A : Type) [CommRing A] : Prop extends
  IsLocalRing A, IsNoetherianRing A where
  out (R : Type) [CommRing R] [IsRegularLocalRing R]
    (f : R →+* (AdicCompletion (maximalIdeal A) A)) (h : IsLocalHom f) (h' : Function.Surjective f) :
      ∃ (rs : List R), RingTheory.Sequence.IsRegular R rs ∧ RingHom.ker f = Ideal.ofList rs

/--
Let  $R$  be a regular local ring and  $I \subset R$  an ideal such that
 $R/I$  is Gorenstein but not a local complete intersection.
Show that  $I$  cannot have height 0 or 1.
-/
theorem IsLocalRing.not_isCompleteIntersection.height_not_zero_and_not_one (B : Type) [CommRing B]
  [IsRegularLocalRing B] (I : Ideal B) [IsGorensteinRing (B / I)]
  (hc : ¬ IsLocalCompleteIntersectionRing (B / I)) : I.height ≠ 0 ∧ I.height ≠ 1 := by
  sorry

end Problem79

```

Exercise (80). Consider the ideal $I \subset k[x_1, \dots, x_6]$ generated by the following polynomials:

$$\begin{aligned}
 f_1 &= x_2x_4 + x_3x_6, \\
 f_2 &= x_3x_5 + x_1x_6, \\
 f_3 &= x_1x_2 - x_2x_5 + x_3x_5 - x_5x_6, \\
 f_4 &= x_2x_3 + x_2x_4 + x_2x_6 + x_6^2, \\
 f_5 &= x_3^2 + x_3x_4 + x_3x_6 - x_4x_6, \\
 f_6 &= x_1x_3 + x_1x_4 + x_4x_5 + x_1x_6.
 \end{aligned}$$

Prove that R/I is Cohen–Macaulay of dimension 3.

```

import Mathlib

namespace Problem80

section

open CategoryTheory Abelian Problem80

variable {R : Type} [CommRing R]

instance : CategoryTheory.HasExt.{0} (ModuleCat.{0} R) :=
  CategoryTheory.hasExt_of_enoughProjectives (ModuleCat R)

noncomputable def moduleDepth (N M : ModuleCat.{0} R) :  $\mathbb{N}_\infty$  :=
  sSup {n :  $\mathbb{N}_\infty$  |  $\forall i : \mathbb{N}, i < n \rightarrow \text{Subsingleton } (\text{CategoryTheory.Abelian.Ext}\{0\} \text{ N M } i)$ }

noncomputable def Ideal.depth (I : Ideal R) (M : ModuleCat.{0} R) :  $\mathbb{N}_\infty$  :=
  moduleDepth (ModuleCat.of R (R / I)) M

noncomputable def IsLocalRing.depth [IsLocalRing R] (M : ModuleCat.{0} R) :  $\mathbb{N}_\infty$  :=
  (IsLocalRing.maximalIdeal R).depth M

variable (R)

class IsCohenMacaulayLocalRing : Prop extends IsLocalRing R where
  depth_eq_dim : ringKrullDim R = IsLocalRing.depth (ModuleCat.of R R)

class IsCohenMacaulayRing : Prop where
  CM_localize :  $\forall p : \text{Ideal } R, \forall (- : p.\text{IsPrime}), \text{IsCohenMacaulayLocalRing } (\text{Localization.AtPrime } p)$ 

end

open MvPolynomial

abbrev target_ring_aux (k : Type) [Field k] :=
  (MvPolynomial (Fin 6) k) / Ideal.span ({
    X 1 * X 3 + X 2 * X 5, X 2 * X 4 + X 0 * X 5, X 0 * X 1 - X 1 * X 4 + X 2 * X 4 - X 4 * X 5,
    X 1 * X 2 + X 1 * X 3 + X 1 * X 5 + (X 5)^2, (X 2)^2 + X 2 * X 3 + X 2 * X 5 - X 3 * X 5,
    X 0 * X 2 + X 0 * X 3 + X 3 * X 4 + X 0 * X 5} : Set (MvPolynomial (Fin 6) k))

/--
Consider the ideal  $\langle I \subset k[x_1, \dots, x_6] \rangle$  generated by the following polynomials:
\begin{aligned}
f_1 &= x_2x_4 + x_3x_6, \\
f_2 &= x_3x_5 + x_1x_6, \\
f_3 &= x_1x_2 - x_2x_5 + x_3x_5 - x_5x_6, \\
f_4 &= x_2x_3 + x_2x_4 + x_2x_6 + x_6^2, \\
f_5 &= x_3^2 + x_3x_4 + x_3x_6 - x_4x_6, \\
f_6 &= x_1x_3 + x_1x_4 + x_4x_5 + x_1x_6.
\end{aligned}
\]

```

```

Prove that  $(R/I)$  is Cohen-Macaulay of dimension  $(3)$ .
-/
theorem isCohenMacaulayRing_of_dimension_three (k : Type) [Field k] :
  IsCohenMacaulayRing (target_ring_aux k)  $\wedge$  (ringKrullDim (target_ring_aux k) = 3) := by
  sorry
end Problem80

```

Exercise (81). Let A be a local Noetherian ring, $I \subset A$ an ideal. Show that I is generated by a regular sequence if and only if I/I^2 is free over A/I and $\text{pd}_A I < \infty$.

```

import Mathlib

namespace Problem81

/--
Let  $(A)$  be a local Noetherian ring,  $(I \subset A)$  an ideal. Show that
 $(I)$  is generated by a regular sequence if and only if  $(I/I^2)$  is free over  $(A/I)$  and
 $\text{pd}_A I < \infty$ .
-/
theorem generated_by_regular_sequence_iff (R : Type) [CommRing R] [IsLocalRing R]
  [IsNoetherianRing R] (I : Ideal R) (netop : I  $\neq$   $\tau$ ) :
   $\exists$  (rs : List R), (RingTheory.Sequence.IsRegular R rs)  $\wedge$  Ideal.ofList rs = I  $\leftrightarrow$ 
  Module.Free (R / I) I.Cotangent  $\wedge$ 
  ( $\exists$  n, CategoryTheory.HasProjectiveDimensionLE (ModuleCat.of R I) n) := by
  sorry
end Problem81

```

Exercise (82). Let A be a Noetherian complete local ring of dimension d , of mixed characteristic (i.e., $\text{Char} A = 0$ and $\text{Char} A/\mathfrak{m}$), and let $p = \text{char}(A/\mathfrak{m})$. Assume that $\text{ht}(p \cdot A) = 1$. Prove that A is a finitely generated module over a subring $B \subset A$ such that

$$B \cong C[[x_1, \dots, x_{d-1}]],$$

where C is a discrete valuation ring (DVR).

```

import Mathlib

namespace Problem82

open IsLocalRing

/--
Let  $(A)$  be a Noetherian complete local ring of dimension  $(d)$ , of mixed characteristic
(i.e.,  $\text{Char} A = 0$  and  $\text{Char} A / \mathfrak{m} = p$ ), and let
 $(p = \text{char}(A/\mathfrak{m}))$ . Assume that  $(\text{ht}(p \cdot A) = 1)$ .
Prove that  $(A)$  is a finitely generated module over a subring  $(B \subset A)$  such that

```

```

\[[
B \cong C[[x_1, \dots, x_{d-1}]],
\]
where \((C)\) is a discrete valuation ring (DVR).
-/
theorem subring_iso_mvPowerSeries_over_DVR (d : ℕ) (A : Type) [CommRing A] [IsLocalRing A]
[IsNoetherianRing A] [IsAdicComplete (maximalIdeal A) A] (dim : ringKruLLDim A = d)
{p : ℕ} (hp : p.Prime) [CharZero A] [CharP (ResidueField A) p]
(ht : (Ideal.span {(p : A)}).height = 1) :
  ∃ B : Subring A, Module.Finite B A ∧
  ∃ (C : Type) (C : CommRing C) (C : IsDomain C), IsDiscreteValuationRing C ∧
  Nonempty (B ≃+ MvPowerSeries (Fin (d - 1)) C) := by
  sorry
end Problem82

```

Exercise (83). Let $f: A \rightarrow B$ be a flat local homomorphism of Noetherian rings, having maximal ideals \mathfrak{M}_A and \mathfrak{M}_B respectively. Prove that if A and $B/\mathfrak{M}_A B$ are regular, then B is regular.

```

import Mathlib

namespace Problem83

open IsLocalRing

/--
A commutative local noetherian ring  $R$  is regular if  $\dim m/m^2 = \dim R$ .
-/
class IsRegularLocalRing (R : Type) [CommRing R] : Prop extends
  IsLocalRing R, IsNoetherianRing R where
  reg : Module.frank (ResidueField R) (CotangentSpace R) = ringKruLLDim R

/--
Let  $(f: A \rightarrow B)$  be a flat local homomorphism of Noetherian rings,
having maximal ideals  $(\mathfrak{M}_A)$  and  $(\mathfrak{M}_B)$  respectively.
Prove that if  $(A)$  and  $(B/\mathfrak{M}_A B)$  are regular, then  $(B)$  is regular.
-/
theorem IsRegularLocalRing.flat_local_of_regular {A B : Type} [CommRing A] [CommRing B]
[IsRegularLocalRing A] [IsNoetherianRing B] [IsLocalRing B] {f : A →+ B} (hfl : IsLocalHom f)
(hff : f.Flat) [IsRegularLocalRing (B / (maximalIdeal A).map f)] : IsRegularLocalRing B := by
  sorry
end Problem83

```

Exercise (84). For a projective module M over a commutative ring R , there exists a free R -module N , such that $M \oplus N$ is free.

```

import Mathlib

```

```

namespace Problem84

/--
For a projective module  $M$  over a commutative ring  $R$ ,
there exists a free  $R$ -module  $N$ , such that  $M \oplus N$  is free.
-/
theorem exists_directSum_free_free_of_projective (R M : Type) [CommRing R] [AddCommGroup M]
  [Module R M] [Module.Projective R M] :  $\exists$  (N : Type) ( $\_ : \text{AddCommGroup } N$ ) ( $\_ : \text{Module } R \ N$ ),
  Module.Free R N  $\wedge$  Module.Free R (N  $\times$  M) := by
  sorry

end Problem84

```

Exercise (85). *There exists a transfinite Euclidean domain such that it cannot be given a Euclidean norm taking value in \mathbb{N} .*

```

import Mathlib

namespace Problem85

/--
Definition of a Euclidean norm taking value in  $\mathbb{N}$ .
-/
class EuclideanNormNat (R : Type) [CommRing R] extends Nontrivial R where
  quotient : R  $\rightarrow$  R  $\rightarrow$  R
  quotient_zero :  $\forall$  a, quotient a 0 = 0
  remainder : R  $\rightarrow$  R  $\rightarrow$  R
  quotient_mul_add_remainder_eq :  $\forall$  a b, b  $\neq$  0  $\rightarrow$  quotient a b + remainder a b = a
  norm : R  $\rightarrow$   $\mathbb{N}$ 
  remainder_lt :  $\forall$  (a) {b}, b  $\neq$  0  $\rightarrow$  norm (remainder a b) < norm b
  mul_left_not_lt :  $\forall$  (a) {b}, b  $\neq$  0  $\rightarrow$   $\neg$  norm (a * b) < norm a

/--
There exists a transfinite Euclidean domain such that it cannot be given a Euclidean norm taking
value in  $\mathbb{N}$ .
-/
theorem exist_euclideanDomain_not_norm_nat :
   $\exists$  (R : Type) ( $\_ : \text{EuclideanDomain } R$ ), IsEmpty (EuclideanNormNat R) := by
  sorry

end Problem85

```

Exercise (86). *For a commutative ring A , $\dim A[x, y] + \dim A \leq 2 * \dim A[x]$.*

```

import Mathlib

namespace Problem86

/--
For a commutative ring  $A$ ,  $\dim A[x, y] + \dim A \leq 2 * \dim A[x]$ .

```

```

-/
theorem dimension_convex (A : Type) [CommRing A] :
  ringKrullDim (MvPolynomial (Fin 2) A) + ringKrullDim A ≤ 2 * ringKrullDim (Polynomial A) := by
  sorry
end Problem86

```

Exercise (87). *There exists two commutative rings R, S , such that $R[x]$ is isomorphic to $S[x]$ but R is not isomorphic to S .*

```

import Mathlib

namespace Problem87

/--
There exists two commutative rings  $\backslash(R, S\backslash)$ , such that  $\backslash(R[x]\backslash)$  is isomorphic to  $\backslash(S[x]\backslash)$  but  $\backslash(R\backslash)$ 
is not isomorphic to  $\backslash(S\backslash)$ .
-/
theorem exists_polynomial_ringEquiv_isEmpty_ringEquiv :
  ∃ (R S : Type) (R : CommRing R) (S : CommRing S),
  Nonempty ((Polynomial R) ≃+* (Polynomial S)) ∧ IsEmpty (R ≃+* S) := by
  sorry
end Problem87

```

Exercise (88). $\mathbb{C}[x, y, z]/(x^2 + y^3 + z^7)$ is a UFD.

```

import Mathlib

namespace Problem88

/--
The ring  $\mathbb{C}[x, y, z] / (x^2 + y^3 + z^7)$ .
-/
abbrev R : Type := (MvPolynomial (Fin 3) ℂ) / Ideal.span {(.X 0 ^ 2 + .X 1 ^ 3 + .X 2 ^ 7 :
  MvPolynomial (Fin 3) ℂ)}

/--
 $\mathbb{C}[x, y, z] / (x^2 + y^3 + z^7)$  is a UFD.
-/
theorem quotient_not_UFD :
  ∃ (h : IsDomain R),
  (UniqueFactorizationMonoid R) := by
  sorry
end Problem88

```

Exercise (89). *Prove that if $\#G = 336$ then G is not simple.*

```

import Mathlib

namespace Problem89

/--
Prove that if  $\#G = 336$  then  $G$  is not simple.
-/
theorem not_isSimpleGroup_of_card_eq_336 (G : Type) [Group G]
  [Finite G] (h_card : Nat.card G = 336) : ¬ IsSimpleGroup G := by
  sorry

end Problem89

```

Exercise (90). *Given a field k , there exists some $n > 0$, there exists some subfield $K \subseteq k(x_1, \dots, x_n)$, such that $K \cap k[X_1, \dots, x_n]$ is not a finitely generated k -algebra.*

```

import Mathlib

namespace Problem90

/--
Given a field  $k$ , there exists some  $n > 0$ , there exists some subfield
 $K \subseteq k(x_1, \dots, x_n)$ , such that  $K \cap k[X_1, \dots, x_n]$  is not a finitely
generated  $k$ -algebra.
-/
theorem not_finiteType_inf_algebraMap_range (k : Type) [Field k] :
  ∃ (n : ℕ) (K : IntermediateField k (FractionRing (MvPolynomial (Fin n) k))),
  ¬ Algebra.FiniteType k (K.toSubalgebra ∩ (Algebra.algHom k (MvPolynomial (Fin n) k)
    (FractionRing (MvPolynomial (Fin n) k))).range :
    Subalgebra k (FractionRing (MvPolynomial (Fin n) k))) := by
  sorry

end Problem90

```

Exercise (91). *Let k be a field, $A := k[x, y]/(xy(x + y - 1))$, then $\text{Pic } A \cong k^\times$.*

```

import Mathlib

namespace Problem91

open CategoryTheory MvPolynomial

/--
The Picard group of a commutative ring  $R$  consists of the invertible  $R$ -modules,
up to isomorphism.
-/
abbrev CommRing.Pic (R : Type) [CommRing R] : Type 1 := (Skeleton <| ModuleCat.{0} R)*

/--

```

```

Let $ k $ be a field, $ A := k[x, y]/(xy(x + y - 1)) $, then $ \mathrm{Pic} A \cong k^{\times} $.
-/
theorem pic_three_lines {k : Type} [Field k] : Nonempty <|
  CommRing.Pic (MvPolynomial (Fin 2) k / Ideal.span ({(X 0) * (X 1) * (X 0 + X 1 - 1)} :
    Set (MvPolynomial (Fin 2) k))) ≈* kx := by
  sorry
end Problem91

```

Exercise (92). Let A be a commutative ring with identity, $\dim A = 1$. Then all possible sequences for $a_n = \dim A[x_1, \dots, x_n] (n \in \mathbb{N})$ are exactly the sequences of the form: $a_n = 2n + 1$ if $n \leq k$ else $a_n = n + k + 1$, for some $k \in \mathbb{N} \cup \{+\infty\}$.

```

import Mathlib

namespace Problem92

/--
\((a_n = 2n+1)\) if \((n \leq k)\) else \((a_n = n + k + 1)\), for some \((k \in \mathbb{N} \cup \{+\infty\})\).
-/
def a (k : ℕ∞) (n : ℕ) :=
  if h : n ≤ k then 2 * n + 1
  else n + WithTop.untop k (by rintro rfl; exact h.le_top) + 1

/--
Let $A$ be a commutative ring with identity, $\dim A = 1$.
Then all possible sequences for \((a_n = \dim A[x_1, \dots, x_n] \ (n \in \mathbb{N}))\) are exactly
the sequences of the form: \((a_n = 2n+1)\) if \((n \leq k)\) else \((a_n = n + k + 1)\), for some
\((k \in \mathbb{N} \cup \{+\infty\})\).
-/
theorem dimension_sequences_of_one_dimensional_rings :
  (∀ (A : Type) [CommRing A] (h : ringKrullDim A = 1),
    ∃ (k : ℕ∞), (∀ (n : ℕ), ringKrullDim (MvPolynomial (Fin n) A) = a k n)) ∧
  (∀ (k : ℕ), ∃ (A : Type) (_ : CommRing A) (h : ringKrullDim A = 1),
    (∀ (n : ℕ), ringKrullDim (MvPolynomial (Fin n) A) = a k n)) := by
  sorry
end Problem92

```

Exercise (93). There exists a field k and a (not necessarily commutative) ring A such that A is integral and finitely generated over k but $\dim_k A$ is not finite.

```

import Mathlib

namespace Problem93

/--
There exists a field $k$ and a (not necessarily commutative) ring $A$
such that $A$ is integral and finitely generated over $k$ but $\dim_k A$ is not finite.

```

```

-/
theorem exists_integral_finiteType_not_finiteDimensional : ∃ (k A : Type) (k : Field k)
  (A : Ring A) (A : Algebra k A),
  Algebra.IsIntegral k A ∧ Algebra.FiniteType k A ∧ ¬ FiniteDimensional k A := by
  sorry
end Problem93

```

Exercise (94). Let k be field, $\text{char } k = 0$, A be a finite-type k -algebra, $f : A \rightarrow A$ be an étale endomorphism, $\varphi : A \rightarrow k$, $I \subset A$ be a ideal. If A is a domain, then

$$\{n \in \mathbb{N} \mid \varphi \circ f^n|_I = 0\}$$

is either finite or contains an arithmetic progression with a positive common difference.

```

import Mathlib

namespace Problem94

variable {k A : Type} [Field k] [CharZero k] [CommRing A] [IsDomain A] [Algebra k A]
  [Algebra.FiniteType k A] (f : A →A[k] A) (φ : A →A[k] k) (I : Ideal A)

/--
The set  $\{n \in \mathbb{N} \mid \varphi \circ f^n|_I = 0\}$ .
-/
def zeroSet : Set ℕ := {n | ∀ x : I, (φ.comp (f ^ n)) (x : A) = 0}

/--
Let  $k$  be field,  $\text{char } k = 0$ ,  $A$  be a finite-type  $k$ -algebra,  $f : A \rightarrow A$  be an
'étale endomorphism,  $\varphi : A \rightarrow k$ ,  $I \subset A$  be a ideal. If  $A$  is a domain,
then  $\{n \in \mathbb{N} \mid \varphi \circ f^n|_I = 0\}$ 
is either finite or contains an arithmetic progression with a positive common difference.
-/
theorem zeroSet_finite_or_contain_arithmetic_progression (hf : f.FormallyEtale) :
  (zeroSet f φ I).Finite ∨ ∃ (d : ℕ+) (a : ℕ), ∀ n : ℕ, a + d * n ∈ zeroSet f φ I := by
  sorry
end Problem94

```

Exercise (95). Let $f : \mathbb{C}[x, y] \rightarrow \mathbb{C}[x, y]$, $x \mapsto p(x) + ay$, $y \mapsto x$, where $a \in \mathbb{C}$, $a \neq 0$, $p(x) \in \mathbb{C}[x]$ have degree > 1 , $\mathfrak{p} \subset \mathbb{C}[x, y]$ be a prime ideal. If $\text{height } \mathfrak{p} = 1$, then $f(\mathfrak{p}) \neq \mathfrak{p}$.

```

import Mathlib

namespace Problem95

open Polynomial Bivariate

/--

```

```

Let $f : \mathbb{C}[x, y] \to \mathbb{C}[x, y]$, $x \mapsto p(x) + ay$, $y \mapsto x$,
where $a \in \mathbb{C}$, $p(x) \in \mathbb{C}[x]$.
-/
noncomputable
def f (a : ℂ) (p : ℂ[X]): ℂ[X][Y] →+* ℂ[X][Y] :=
  eval₂RingHom (aeval (a • Y + C p)).toRingHom (C X)

/--
Let $f : \mathbb{C}[x, y] \to \mathbb{C}[x, y]$, $x \mapsto p(x) + ay$, $y \mapsto x$,
where $a \in \mathbb{C}$, $a \neq 0$, $p(x) \in \mathbb{C}[x]$ have degree $>1$, $\mathbb{C}[x, y]_{(p)}$
$\subset \mathbb{C}[x, y]$ be a prime ideal. If $\mathrm{height}(\mathbb{C}[x, y]_{(p)}) = 1$, then
$f(\mathbb{C}[x, y]_{(p)}) \neq \mathbb{C}[x, y]_{(p)}$.
-/
theorem p_map_ne_p (p : ℂ[X]) (h : p.natDegree > 1) {a : ℂ} (ha : a ≠ 0)
  (I : Ideal ℂ[X][Y]) (hI : I.IsPrime) (h : I.height = 1) :
  I.map (f a p) ≠ I := by
  sorry
end Problem95

```

Exercise (96). Let $f(x) \in \mathbb{Q}(x)$ be a rational function of degree at least 2, $\alpha \in \mathbb{Q}$. If the orbit $\mathcal{O}_f(\alpha)$ contains infinitely many integers, then $f^2(x)$ is a polynomial.

```

import Mathlib

namespace Problem96

open RatFunc

/--
Let $f(x) \in \mathbb{Q}(x)$ be a rational function of degree at least 2, $\alpha \in \mathbb{Q}$.
If the orbit $\mathcal{O}_f(\alpha)$ contains infinitely many integers, then $f^2(x)$ is
a polynomial.
-/
theorem ratFunc_square_is_poly_of_orbit_contain_infinite_integer
  {f : RatFunc ℚ} (hf : f.num.natDegree ≥ 2 ∨ f.denom.natDegree ≥ 2) {a : ℚ}
  (h : ∀ n : ℕ, (f.eval (RingHom.id ℚ))^n a ≠ 0) -- exclude the case that the `denom` is zero
  (ha : {m : ℤ | ∃ n : ℕ, m = (f.eval (RingHom.id ℚ))^n a}.Infinite) :
  ∃ g : Polynomial ℚ, g = f.eval C f := by
  sorry
end Problem96

```

Exercise (97). If k is a field of characteristic zero, $n \in \mathbb{N}$, $n \neq 0$, and $\phi: k[x_1, \dots, x_n] \rightarrow k[x_1, \dots, x_n]$ is given by $(x_1, \dots, x_n) \mapsto (f_1(x_1), \dots, f_n(x_n))$, where $f_i(x_i) \in k[x_i]$ having degree at least two, then there is a point $a \in k^n$ such that for any non-zero polynomial $p \in k[x_1, \dots, x_n]$, there exists $m \in \mathbb{N}$ such that $p(\phi^m(a)) \neq 0$.

```

import Mathlib

namespace Problem97

open scoped Polynomial

/--
If  $k$  is a field of characteristic zero,  $n \in \mathbb{N}$ ,  $n \neq 0$ ,
and  $\phi : k[x_1, \dots, x_n] \rightarrow k[x_1, \dots, x_n]$  is given by  $(x_1, \dots, x_n) \mapsto (f_1(x_1), \dots, f_n(x_n))$ , where  $f_i(x_i) \in k[x_i]$  having degree at least two, then there
is a point  $a \in k^n$  such that for any non-zero polynomial  $p \in k[x_1, \dots, x_n]$ ,
there exists  $m \in \mathbb{N}$  such that  $p(\phi^m(a)) \neq 0$ .
-/
theorem exists_point_not_in_zero_set {τ k : Type} [Finite τ] [Nonempty τ] [Field k] [CharZero k]
  {f : τ → k[X]} (hfd : ∀ i : τ, (f i).natDegree ≥ 2) : ∃ a : τ → k,
    ∀ p : MvPolynomial τ k, p ≠ 0 →
      ∃ m : ℕ, ((MvPolynomial.aeval (fun i ↦ (f i).toMvPolynomial i)) ^ m) p).aeval a ≠ 0 := by
  sorry

end Problem97

```

Exercise (98). If K be a number field, A be a finite-type K -algebra, $f : A \rightarrow A$ be an endomorphism. If A is a domain and f is not of finite order, then there exists a maximal ideal $m \subset A$ such that for all $n \in \mathbb{N}_+$, $f^{-n}(m) \neq m$.

```

import Mathlib

namespace Problem98

/--
If  $K$  be a number field,  $A$  be a finite-type  $K$ -algebra,  $f : A \rightarrow A$  be an endomorphism.
If  $A$  is a domain and  $f$  is not of finite order, then there exists a maximal ideal  $m \subset A$ 
such that for all  $n \in \mathbb{N}_+$ ,  $f^{-n}(m) \neq m$ .
-/
theorem exists_maximal_ideal_not_in_finite_order {K A : Type} [Field K] [NumberField K] [CommRing A]
  [IsDomain A] [Algebra K A] [Algebra.FiniteType K A] {f : A →a [K] A} (hf : ∀ n > 0, f ^ n ≠ 1) :
  ∃ m : Ideal A, m.IsMaximal ∧ ∀ n > 0, m.comap (f ^ n) ≠ m := by
  sorry

end Problem98

```

Exercise (99). Let A be a finite-type \mathbb{C} -algebra, $n \in \mathbb{N}$, $n \geq 1$. If A is a domain, and $\text{Aut}_{\mathbb{C}} A$ is isomorphic to $\text{Aut}_{\mathbb{C}} \mathbb{C}[x_1, \dots, x_n]$, then A is isomorphic to $\mathbb{C}[x_1, \dots, x_n]$ as \mathbb{C} -algebras.

```

import Mathlib

namespace Problem99

```

```

/--
Let  $A$  be a finite-type  $\mathbb{C}$ -algebra,  $n \in \mathbb{N}$ ,  $n \geq 1$ . If  $A$  is a domain,
and  $\mathrm{Aut}_{\mathbb{C}} A$  is isomorphic to  $\mathrm{Aut}_{\mathbb{C}} \mathbb{C}[x_1, \dots, x_n]$ , then  $A$  is isomorphic to  $\mathbb{C}[x_1, \dots, x_n]$  as
 $\mathbb{C}$ -algebras.
-/
theorem equiv_of_aut_equiv {A : Type} [CommRing A] [IsDomain A] [Algebra  $\mathbb{C}$  A]
  [Algebra.FiniteType  $\mathbb{C}$  A] {n :  $\mathbb{N}$ } (hn : n ≥ 1)
  (e : (A  $\simeq_{\mathbb{C}}$  A)  $\simeq^*$  (MvPolynomial (Fin n)  $\mathbb{C}$   $\simeq_{\mathbb{C}}$  MvPolynomial (Fin n)  $\mathbb{C}$ )) :
  Nonempty (A  $\simeq_{\mathbb{C}}$  MvPolynomial (Fin n)  $\mathbb{C}$ ) := by
  sorry

end Problem99

```

Exercise (100). Let R be a Noetherian ring, P be a countably generated projective R -module such that $P_{\mathfrak{m}}$ has infinite rank for all maximal ideals \mathfrak{m} of R . Then P is free.

```

import Mathlib

namespace Problem100

open Module

/--
Let  $R$  be a Noetherian ring,  $P$  be a countably generated projective  $R$ -module
such that  $P_{\mathfrak{m}}$  has infinite rank for all maximal ideals  $\mathfrak{m}$  of  $R$ .
Then  $P$  is free.
-/
theorem free_of_countably_generated_projective_of_local_infinite_rank {R : Type} [CommRing R]
  [IsNoetherianRing R] (P : Type) [AddCommGroup P] [Module R P] [Projective R P]
  (hcg :  $\exists s : \text{Set } P, s.\text{Countable} \wedge \text{Submodule.span } R s = \tau$ )
  (hm :  $\forall m : \text{Ideal } R, (\_ : m.\text{IsMaximal}) \rightarrow$ 
     $\neg \text{Module.Finite } (\text{Localization.AtPrime } m) (\text{LocalizedModule.AtPrime } m P)) : \text{Free } R P := by
  sorry

end Problem100$ 
```