Title

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1.1 Proof of Nullstellensatz 3

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Let $k = \bar{k}$ and R a ring containing ideals I, J.

Definition 1.0.1 (Radical)**.**
Recall that the *radical* of I is defined as

$$\sqrt{I} = \left\{ r \in R \;\middle|\; r^k \in I \text{ for some } k \in \mathbb{N} \right\}.$$

Example 1.1.
Let $I = (x_1, x_2^2) \subset \mathbb{C}[x_1, x_2]$, so $I = \left\{ f_1 x_1 + f_2 x_2 \;\middle|\; f_1, f_2 \in \mathbb{C}[x_1, x_2] \right\}$. Then $\sqrt{I} = (x_1, x_2)$, since $x_2^2 \in I \implies x_2 \in \sqrt{I}$.

Given $f \in k[x_1, \cdots, x_n]$, take its value at $a = (a_1, \cdots, a_n)$ and denote it $f(a)$. Set $\deg(f)$ to be the largest value of $i_1 + \cdots + i_n$ such that the coefficient of $\prod x_j^{i_j}$ is nonzero.

Example 1.2.
$\deg(x_1 + x_2^2 + x_1 x_2^3 = 4)$

Definition 1.0.2 (Affine Variety)**.**

1. Affine n-space $\mathbb{A}^n = \mathbb{A}_k^n$ is defined as $\left\{ (a_1, \cdots, a_n) \;\middle|\; a_i \in k \right\}$.

   Remark: not k^n, since we won't necessarily use the vector space structure (e.g. adding points).

2. Let $S \subset k[x_1, \cdots, x_n]$ to be a set of polynomials. Then define $V(S) = \left\{ x \in \mathbb{A}^n \;\middle|\; f(x) = 0 \right\} \subset \mathbb{A}^n$ to be an *affine variety*.

Example 1.3.

- $\mathbb{A}^n = V(0)$.
- For any point $(a_1, \cdots, a_n) \in \mathbb{A}^n$, then $V(x_1 - a_1, \cdots, x_n - a_n) = \{a_1, \cdots, a_n\}$ uniquely determines the point.
- For any finite set $r_1, \cdots, r_k \in \mathbb{A}^1$, there exists a polynomial $f(x)$ whose roots are r_i.

Remark 1.
We may as well assume S is an ideal by taking the ideal it generates, $S \subseteq \langle S \rangle = \left\{ \sum g_i f_i \;\middle|\; g_i \in k[x_1, \cdots, x_n],\, f_i \in S \right\}$. Then $V(\langle S \rangle) \subset V(S)$.

Conversely, if f_1, f_2 vanish at $x \in \mathbb{A}^n$, then $f_1 + f_2, gf_1$ also vanish at x for all $g \in k[x_1, \cdots, x_n]$. Thus $V(S) \subset V(\langle S \rangle)$.

Lemma 1.1.

1. If $S_1 \subseteq S_2$ then $V(S_1) \subseteq V(S_2)$.
2. $V(S_1 \cup S_2) = V(S_1 S_2) = V(S_1) \cap V(S_2)$.

We thus have a map

$$V : \{\text{Ideals in } k[x_1, \cdots, x_n]\} \longrightarrow \{\text{Affine varieties in } \mathbb{A}^n\}.$$

Definition 1.1.1 (The Ideal of a Set)**.**
Let $X \subset \mathbb{A}^n$ be any set, then *the ideal of* X is defined as

$$I(X) \coloneqq \left\{ f \in k[x_1, \cdots, x_n] \;\middle|\; f(x) = 0 \,\forall x \in X \right\}.$$

Example 1.4.
Let X be the union of the x_1 and x_2 axes in $\mathbb{A}^2$, then $I(X) = (x_1 x_2) = \left\{ x_1 x_2 g \;\middle|\; g \in k[x_1, x_2] \right\}$.

Note that if $X_1 \subset X_2$ then $I(X_1) \subset I(X_2)$.

Proposition 1.2 ***(The Image of V is Radical).***
$I(X)$ is a radical ideal, i.e. $I(X) = \sqrt{I(X)}$.
This is because $f(x)^k = 0 \forall x \in X$ implies $f(x) = 0$ for all $x \in X$, so $f^k \in I(X)$ and thus $f \in I(X)$.

Our correspondence is thus

$$\left\{\text{Ideals in } k[x_1, \cdots, x_n]\right\} \xrightarrow{V} \left\{\text{Affine Varieties}\right\}$$
$$\left\{\text{Radical Ideals}\right\} \xleftarrow{I} \left\{?\right\}.$$

Proposition 1.3 ***(Hilbert Nullstellensatz (Zero Locus Theorem)).***

a. For any affine variety X, $V(I(X)) = X$.
b. For any ideal $J \subset k[x_1, \cdots, x_n]$, $I(V(J)) = \sqrt{J}$.

Thus there is a bijection between radical ideals and affine varieties.

1.1 Proof of Nullstellensatz

Remark 2.
Recall the Hilbert Basis Theorem: any ideal in a finitely generated polynomial ring over a field is again finitely generated.

We need to show 4 inclusions, 3 of which are easy.

a: $X \subset V(I(X))$:

- If $x \in X$ then $f(x) = 0$ for all $f \in I(X)$.
- So $x \in V(I(X))$, since every $f \in I(X)$ vanishes at x.

b: $\sqrt{J} \subset I(V(J))$:

- If $f \in \sqrt{J}$ then $f^k \in J$ for some k.
- Then $f^k(x) = 0$ for all $x \in V(J)$.
- So $f(x) = 0$ for all $x \in V(J)$.
- Thus $f \in I(V(J))$.

c: $V(I(X)) \subset X$:

- Need to now use that X is an affine variety.
  - Counterexample: $X = \mathbb{Z}^2 \subset \mathbb{C}^2$, then $I(X) = 0$. But $V(I(X)) = \mathbb{C}^2$, but $\mathbb{C}^2 \not\subset \mathbb{Z}^2$.
- By (b), $I(V(J)) \supset \sqrt{J} \supset J$.
- Since $V(\,\cdot\,)$ is order-reversing, taking V of both sides reverses the containment.
- So $V(I(V(J))) \subset V(J)$, i.e. $V(I(X)) \subset X$.

d: $I(V(J)) \subset \sqrt{J}$ (hard direction)

Theorem 1.4 ***(1st Version of Nullstellensatz).***
Suppose k is algebraically closed and uncountable (still true in countable case by a different proof).
Then the maximal ideals in $k[x_1, \cdots, x_n]$ are of the form $(x_1 - a_1, \cdots, x_n - a_n)$.

Proof .
Let $\mathfrak{m}$ be a maximal ideal, then by the Hilbert Basis Theorem, $\mathfrak{m} = \langle f_1, \cdots, f_r\rangle$ is finitely generated.
Let $L = \mathbb{Q}[\{c\}_i]$ where the c_i are all of the coefficients of the f_i if char $(K) = 0$, **or** $\mathbb{F}_p[\{c\}_i]$ if char $(k) = p$. Then $L \subset k$.
Define $\mathfrak{m}_0 = \mathfrak{m} \cap L[x_1, \cdots, x_n]$. Note that by construction, $f_i \in \mathfrak{m}_0$ for all i, and we can write $\mathfrak{m} = \mathfrak{m}_0 \cdot k[x_1, \cdots, x_n]$.

Claim: $\mathfrak{m}_0$ is a maximal ideal.
If it were the case that

$$\mathfrak{m}_0 \subsetneq \mathfrak{m}_0' \subsetneq L[x_1, \cdots, x_n],$$

then

$$\mathfrak{m}_0 \cdot k[x_1, \cdots, x_n] \subsetneq \mathfrak{m}_0' \cdot k[x_1, \cdots, x_n] \subsetneq k[x_1, \cdots, x_n].$$

So far: constructed a smaller polynomial ring and a maximal ideal in it.

Thus $L[x_1, \cdots, x_n]/\mathfrak{m}_0$ is a field that is finitely generated over either $\mathbb{Q}$ or $\mathbb{F}_p$.

Theorem 1.5 ***(Noether Normalization).***
Any finitely-generated field extension $k_1 \hookrightarrow k_2$ is a finite extension of a purely transcendental extension, i.e. there exist $t_1, \cdots, t_\ell$ such that k_2 is finite over $k_1(t_1, \cdots, t_\ell)$.

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