1 16-04-2018

1.1 Definitions and basic properties of polynomial

$\mathbb{N}$ = set of natural number
$\mathbb{N}_0 = \mathbb{N} \cup \{0\}$
for $n \in \mathbb{N}$, $\mathbb{N}_0^n = \{\alpha = (\alpha_1, \ldots, \alpha_n) | \alpha_1, \ldots, \alpha_n \in \mathbb{N}_0\}$ (is semi-module because closed over addition)

$0 = (0, \ldots, 0)$ and $x_1, \ldots, x_n$; variables
for $\alpha = (\alpha_1, \ldots, \alpha_n) \in \mathbb{N}_0^n$
a mononomial (or direct product of variables) $x^\alpha = \begin{cases} 1 & ,(\text{ if } \alpha = 0) \\ x_1^{\alpha_1}\ x_2^{\alpha_2}\ \ldots x_n^{\alpha_n} & ,(\text{otherwise}) \end{cases}$

K is **field**. [Field : is a set on which addition, subtraction, multiplication, and division are defined, and behave as when they are applied to rational and real numbers.-wikipedia]

Definition 1. *Let $A \subset \mathbb{N}_0^n$: finite*

$$f = \sum_{\alpha \in A} c_\alpha x^\alpha \ (c_\alpha \in K)$$

*is called **a polynomial** of $x_1, \ldots, x_n$ with K-coefficients. It also can be written as*

$$K[x] = K[x_1, \ldots, x_n] = \{f | f \textit{ is a polynomial of } x_1, \ldots, x_n \textit{ with K-coefficients } \}.$$

$$M_n = \{x^\alpha | \alpha \in \mathbb{N}_0^n\} \subset K[x]$$

Example 1. *$n = 2$ then we have $A = \{(0,0), (1,1), (0,3), (2,0), (2,1)\}$.*

$$\textit{For } f = x_1^2 x_2 + 5x_2^3 - 2x_1 x_2 + 10,$$

we can obtain $C_{(2,1)} = 1, C_{(2,0)} = 0, C_{(0,3)} = 5, C_{(1,1)} = -2, C_{(0,0)} = 10$.

Definition 2. ***Support**. $f = \sum_{\alpha \in A} c_\alpha x^\alpha \neq 0$ then*

$$supp(f) = \{\alpha \in A | C_\alpha \neq 0\}$$

Example 2. *$supp(f) = \{(0,0), (1,1), (0,3), (2,1)\}$*

Definition 3. ***Total degree**. $|\alpha| = \alpha_1 + \cdots + \alpha_n,\ (\alpha \in (N)_0^n)$. If $supp(f) \neq \emptyset$*

$$tdeg(f) = max\{|\alpha| \mid \alpha \in supp(f)\}$$

Example 3. *$tdeg(f) = max\{0, 2, 3, 3\} = 3$*

$f, g \in K[x]$
$f\ g$ or associated $\Leftrightarrow \exists C \in K\ \{0\}$ such that $f = c \cdot g$.
For example : $f = x_1^2 x_2 + 1; g = 3x_1^2 x_2 + 3; h = 3x_1^2 x_2 + 2$. Then $f\ g, f not\ h$
$f|g$ or f devides $g \Leftrightarrow \exists h \in K[x]$ such that $f \cdot h = g$

Properties 1. *$f|g \Rightarrow tdeg(f) \leq tdeg(g)$*

Definition 4. *Let $f \in K[x]\ K$. f is **irreducible** if $\Big(h|f \Rightarrow (h \in K or h\ f)\Big)$. If $tdeg(f) > 0$ and f is not irreducible, then f is called **reducible**.*

Theorem 1. *Let $f \in K[x]\ K$. Then f can be **factorized** as*

1. *$f = c\ g_1^{\beta_1}\ g_2^{\beta_2} \ldots g_n^{\beta_m}$ where $c \in K\ \{0\}$, $\beta_1, \beta_2, \ldots, \beta_m \in \mathbb{N}$, and $g_1, \ldots, g_m$: irreducible, $g_i not\ g_j\ (i \neq j)$*

2. *if $f = c\ g_1^{\beta_1}\ g_2^{\beta_2} \ldots g_m^{\beta_m} = d\ h_1^{\gamma_1}\ h_2^{\gamma_2} \ldots h_l^{\gamma_l}$ (factorization). Then (a) $m = l$, (b) by change of index, $g_1\ h_1, \ldots, g_m\ h_m$.*

We can define $GCD(f, g)$ for $f, g \in K[x]$, $\big((f, g) \neq (0, 0)\big)$

Definition 5. *Let $I \in K[x], I \neq \emptyset$. I is **an ideal** if*

1. *$f, g \in I \Rightarrow f + g \in I$*

2. *$f \in I, r \in K[x] \Rightarrow r \cdot f \in I$*

Definition 6. ***An ideal generated by** $f_1, \ldots, f_m$. Let $f_1, \ldots, f_m \in K[x]\ \{0\}$*

$$< f_1, \ldots, f_m >= \{r_1 f_1 + r_2 f_2 + \cdots + r_m f_m | r_1, r_2, \ldots, r_m \in K[x]\}$$

Properties 2. *$< f_1, \ldots, f_m >$ is an ideal.*

Properties 3. *$0 \in I$ (an ideal)*

Problem : Ideal membership problem. Given $I =< f_1, \ldots, f_m >$ and a polynomial h. Determine $h \in I$ or not !

1.2 Single Variable

Take $n = 1, x = x_1, K[x] = K[x_1]$. For $f \in K[x]$ we define **degree of** f as

$$deg(f) = \begin{cases} tdeg(f), (f \neq 0) \\ -\infty, (f = 0) \end{cases}$$

We define this such that properties below is satisfied.

Properties 4. *Let $f, g \in K[x]$.*

1. $deg(f + g) \leq max\{deg(f), deg(g)\}$
2. $deg)(fg) = deg(f) + deg(g)$

Example 4.
1. $f = 2x^2 + 1, g = x + 1$
2. $f = x + 1, g = -x$
3. $f = x + 1, g = 0$

Theorem 2. ***Division Principle***. *Let $f, g \in K[x]$ and $g \neq 0$. Then there exist unique polynomials q, r such that*

$$f = q \cdot g + r$$

*and $deg(r) < deg(g)$ where q is **quotient** and r is **remainder**.*

Example 5. $f = x^3 + x - 1, g = 2x^2 - 1$. *Then* $f = x^3 + x - 1 = \frac{1}{2}x(2x^2 - 1) + \frac{3}{2}x - 1$ *with* $deg(g) = 2, deg(r) = 1$

2 23-04-2018

Definition 7. *Let* $f \in K[x_1],\ f \neq 0$. f *is* ***monic*** $\Leftrightarrow f = x^{deg\ f} +$ *(lower terms).*