$(2) \Rightarrow (3)$:   trivial.

$(3) \Rightarrow (1)$:   By (3) we have $\mathrm{in}\,(Q) \in\, <\mathrm{in}\,(F)>$ for every $Q \in J - \{0\}$. Hence $<\mathrm{in}\,(J)> \,=\, <\mathrm{in}\,(F)>$.

**2.6.  COROLLARY.** *Let  F  be a Gröbner basis of an ideal  $J \leqslant R[X]$.*

1) *F  generates  J.*

2) *Let  $Q \in R[X]$.  Then  $Q \in J$  iff a rest of  Q  after dividing by  F is zero.*

*Proof.*  Obvious.

2.7.  Another caracterisation of Gröbner bases can be given as follows:

We shall say that a set $\{L_\alpha \mid \alpha \in \mathscr{D}(F)\}$ of admissible combinations of $F$ (with pairwise different degrees) is an "$F$-admissible set", if for all $\alpha$ we have $\deg\,(L_\alpha) = \alpha$ and $\mathrm{lc}\,(L_\alpha)$ generates the ideal

$$_R<\mathrm{lc}\,(P) \mid P \in\, <\mathrm{in}\,(F)>,\, \deg\,(P) = \alpha> \,.$$

Any $F$-admissible set is $R$-linearly independent.
If $R$ is a field the condition on $\mathrm{lc}\,(L_\alpha)$ is superfluous.

**PROPOSITION.**  *Let  J  be an ideal in  $R[X]$  containing  F.  Then the following conditions are equivalent:*

(1)   *F  is a Gröbner basis of  J.*

(2)   *There is an F-admissible set which is a R-basis of  J.*

(3)   *Every F-admissible set is a R-basis of  J.*

*Proof.*  Let $\{L_\alpha \mid \alpha \in \mathscr{D}(F)\}$ be a $F$-admissible set.

$(1) \Rightarrow (3)$:   Let $Q$ be an element of $J - \{0\}$. Division of $Q$ by $\{L_{\deg(Q)}\}$, of its rest $\bar{Q}$ by $\{L_{\deg(\bar{Q})}\}$, ... yields in a finite number of steps an expression of $Q$ as $R$-linear combination of $L_\alpha$'s.

$(3) \Rightarrow (2)$:   trivial.

$(2) \Rightarrow (1)$:   Suppose that $\{L_\alpha \mid \alpha \in \mathscr{D}(F)\}$ is a $R$-basis of $J$. For every $Q \in J - \{0\}$ the initial term of $L_{\deg(Q)}$ divides $\mathrm{in}\,(Q)$, hence $\mathrm{in}\,(Q) \in\, <\mathrm{in}\,(F)>$.

## 3.  CONSTRUCTION OF GRÖBNER BASES

3.1.  *Definition.*  Let $P, Q$ be elements of $R[X]$, let $\alpha, \beta \in \mathbf{N}^n$ and let $a, b \in R$. Then the polynomial

$$S(P, Q) := aX^\alpha P - bX^\beta Q$$

is called a "$S$(ubtraction)-polynomial of $P, Q$" iff

$$\alpha + \deg(P) = \beta + \deg(Q) = \min\left(\mathscr{D}(\{P\}) \cap \mathscr{D}(\{Q\})\right)$$

and $\operatorname{lc}(P) \cdot a = \operatorname{lc}(Q) \cdot b = $ a least common multiple of $\operatorname{lc}(P)$ and $\operatorname{lc}(Q)$.

3.2. *Example.* Consider the graded lexicographic ordering on $\mathbf{N}^2$ and

$$P := 6X_1^3 X_2 + 1, \quad Q := 8X_1 X_2^2 + 3X_1 X_2 + X_2 \in \mathbf{Z}[X_1, X_2].$$

Then

$$4X_2 P - 3X_1^2 Q = -9X_1^3 X_2 - 3X_1^2 X_2 + 4X_2 \quad \text{and} \quad -4X_2 P + 3X_1^2 Q$$
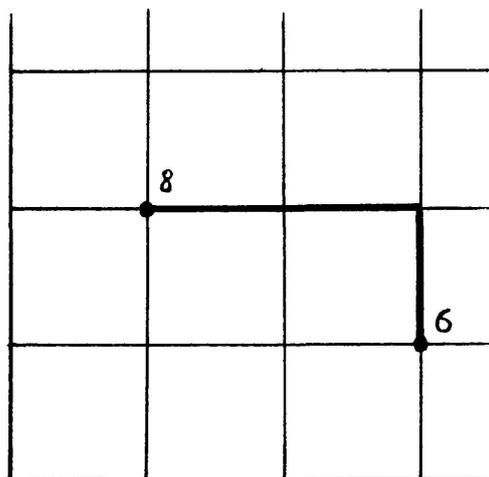
are $S$-polynomials of $P, Q$.

See figure 5.



FIGURE 5.

3.3 *Remark.* For $P, Q \in R[X]$, $S(P, Q)$ as defined above is unique up to multiplication by an invertible element of $R$. Therefore we shall call it "the" $S$-polynomial of $P, Q$.

3.4. LEMMA. *Let* $P_1, ..., P_k \in R[X]$, $c_1, ..., c_k \in R$ *such that* $\deg(P_1) = ...$
$= \deg(P_k) =: \delta$ *but* $\deg\left(\sum_{i=1}^{k} c_i P_i\right) \neq \delta$.

*Then* $\sum_{i=1}^{k} c_i P_i$ *is a $R$-linear combination of the $S$-polynomials* $S(P_i, P_j)$, $1 \leq i, j \leq k$.

*Proof.* By induction on $k$.

Let $l_i := \operatorname{lc}(P_i)$, $1 \leq i \leq k$. Then $\sum_{i=1}^{k} c_i l_i = 0$.

It is sufficient to prove the existence of $a_{ij}, b_{ij} \in R$ such that

$$\sum_{i=1}^{k} c_i P_i = \sum_{1 \leqslant i, j \leqslant k} (a_{ij} P_i - b_{ij} P_j) \quad \text{and} \quad a_{ij} l_i = b_{ij} l_j, \quad 1 \leqslant i, j \leqslant n.$$

For $k = 2$ we have $c_1 P_1 + c_2 P_2 = c_1 P_1 - (-c_2) P_2$ and $c_1 l_1 = (-c_2) l_2$.
$k = 3$: Let $l$ be a greatest common divisor of $l_1, l_2, l_3$. Since $c_2 l_2 = -c_1 l_1 - c_3 l_3$, a greatest common divisor of $l_1$ and $l_3$ divides $c_2 l$. Hence there are elements $x_2, x_3 \in R$ such that $c_2 l = x_1 l_1 + x_3 l_3$.

Then $d_1 := (-x_1 l_2 - c_1 l)/l$, $d_2 := (-x_1 l_1)/l$, $d_3 := (x_3 l_2)/l$ are elements of $R$. Furthermore, we have

$$(c_1 + d_1) l_1 = d_2 l_2$$
$$(c_2 + d_2) l_2 = d_3 l_3$$
$$(c_3 + d_3) l_3 = d_1 l_1 \quad \text{and}$$

$$\sum_{i=1}^{3} c_i P_i = [(c_1 + d_1) P_1 - d_2 P_2] + [(c_2 + d_2) P_2 - d_3 P_3]$$
$$+ [(c_3 + d_3) P_3 - d_1 P_1].$$

$k > 3$: Let $Q := \sum_{i=3}^{k} c_i P_i \quad \text{and} \quad m := \sum_{i=3}^{k} c_i l_i.$

If $m = 0$, we can apply the induction hypothesis to $Q$.

If $m \neq 0$, by the $k = 3$ case there are $d_1, d_2, d_3 \in R$ such that

$$c_1 P_1 + c_2 P_2 + Q = [(c_1 + d_1) P_1 - d_2 P_2] + [(c_2 + d_2) P_2 - d_3 Q]$$
$$+ [(1 + d_3) Q - d_1 P_1]$$

and $(c_1 + d_1) l_1 = d_2 l_2$, $(c_2 + d_2) l_2 = d_3 m$, $(1 + d_3) m = d_1 l_1$.

Therefore, we can apply the induction hypothesis to $(c_2 + d_2) P_2 - \sum_{i=3}^{k} d_3 c_i P_i$

and to $-d_1 P_1 + \sum_{i=3}^{k} (1 + d_3) c_i P_i$ and thus terminate the proof.

*Remark.* If $R$ is a field, the proof is trivial: Let $l_i := \text{lc}(P_i)$ and

$$P_i' := (P_i / l_i), 1 \leqslant i \leqslant k, \quad \text{then} \quad \sum_{i=1}^{k} c_i P_i = c_1 l_1 (P_1' - P_2')$$

$$+ (c_1 l_1 + c_2 l_2)(P_2' - P_3') + \ldots + (\sum_{i=1}^{k-1} c_i l_i)(P_{k-1}' - P_k').$$

*Proof.* By the preceding theorem we only have to show that there is a $k \in \mathbb{N}$ such that $F_k = F_{k+1}$.

If $F_i \subset F_{i+1}$ then $<\text{in}\,(F_i)> \subset\, <\text{in}\,(F_{i+1})>$. Since the strictly ascending sequence $<\text{in}\,(F_0)> \subset\, <\text{in}\,(F_1)> \subset \ldots$ must be finite, there is a $k \in \mathbb{N}$ with $F_k = F_{k+1}$.

3.7. *Example.* Consider the graded lexicographic ordering on $\mathbb{N}^2$ and

$$F := \{P_1 := 2X_1 X_2^2 - X_1,\ P_2 := 3X_1^2 X_2 - X_2\} \subseteq \mathbb{Z}[X_1, X_2].$$

Then

$$F_0 = F \quad \text{and} \quad S(P_1, P_2) = 3X_1 P_1 - 2X_2 P_2 = -3X_1^2 + 2X_2^2$$
$$= \overline{S(P_1, P_2)} = :P_3.$$

So

$$F_1 = \{P_1, P_2, P_3\} \quad \text{and} \quad \overline{S(P_1, P_2)}^{F_1} = 0,$$

$$\overline{S(P_1, P_3)}^{F_1} = 4X_2^4 - 3X_1^2 = :P_4, \quad \overline{S(P_2, P_3)}^{F_1} = 2X_2^3 - X_2 = :P_5.$$

Therefore $F_2 = \{P_1, P_2, P_3, P_4, P_5\}$ and all rests after division by $F_2$ of $S$-polynomials are 0. Hence $F_2$ is a Gröbner basis of the ideal generated by $F$.
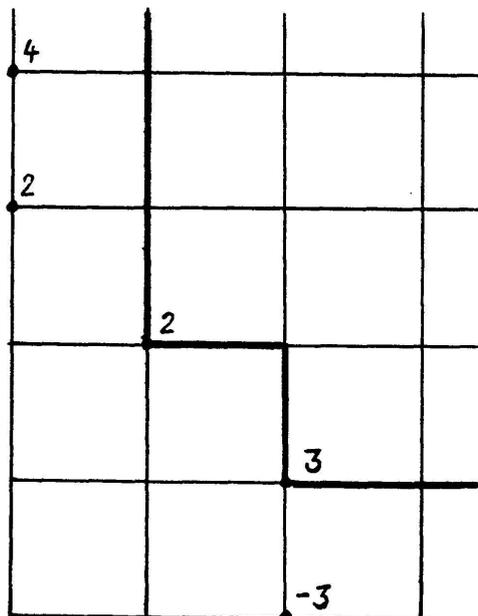
See figure 6.



FIGURE 6.

3.8. *Remark.* Let $G$ be a Gröbner basis of an ideal $J$. We shall say that $G$ is "simplified" if all $P \in G$ fulfill the following two conditions:

$$\mathrm{lc}(P) \text{ generates the ideal } {}_R<\mathrm{lc}(Q) \mid Q \in J, \deg(Q) = \deg(P)>$$

and

$$\mathrm{in}(P) \notin <\mathrm{in}(G-\{P\})> .$$

It is easy to see that the elements of a simplified Gröbner basis have pairwise different degrees.

If $R$ is a field then $G$ is simplified iff the elements of $G$ have pairwise different degrees and $\deg(G)$ is the set of minimal elements (with respect to the natural partial ordering on $\mathbf{N}^n$) in $\deg(J)$.

If $G$ is not simplified, then in the following way we can construct (in a finite number of steps) a simplified Gröbner basis of $J$:

For every $P \in G$ choose an admissible combination $P'$ of $G$ such that $\deg(P) = \deg(P')$ and $\mathrm{lc}(P')$ generates the ideal

$$_R<\mathrm{lc}(Q) \mid Q \in J, \deg(Q) = \deg(P)> .$$

Then $G' := \{P' \mid P \in G\}$ is a Gröbner basis of $J$, since $<\mathrm{in}(J)> = <\mathrm{in}(G)> \subseteq <\mathrm{in}(G')> \subseteq <\mathrm{in}(J)>$.

If there is a $P' \in G'$ with $\mathrm{in}(P') \in <\mathrm{in}(G'-\{P'\})>$, then $G' - \{P'\}$ is a Gröbner basis, since then $<\mathrm{in}(G'-\{P'\})> = <\mathrm{in}(G')> = <\mathrm{in}(J)>$.

Replace $G'$ by $G' - \{P'\}$. After finitely many eliminations of this kind we obtain a simplified Gröbner basis.

In example 3.7. the Gröbner basis $F_2$ is not simplified, since $\mathrm{in}(P_2) = -X_2 \mathrm{in}(P_3)$ and $\mathrm{in}(P_4) = 2X_2 \mathrm{in}(P_5)$. $\{P_1, P_3, P_5\}$ is a simplified Gröbner basis of the ideal generated by $F_2$.

## 4. APPLICATION TO SYSTEMS OF ALGEBRAIC EQUATIONS

Let $J$ be an ideal in $R[X]$, generated by a subset $F \neq \{0\}$.

4.1. We may consider $F$ as a system of algebraic equations in $n$ variables. We denote by $K$ an algebraic closure of the quotient field of $R$.

Let $Z(F)$ (resp. $Z_K(F)$) be the set $\{z \in R^n \text{ (resp. } K^n) \mid P(z) = 0 \text{ for all } P \in F\}$ of common zeros in $R^n$ (resp. $K^n$) of the elements of $F$. Clearly $Z(F) = Z(J)$ and $Z_K(F) = Z_K(J)$.