

A Complete Efficiency Ranking of Decision Making Units in DEA: with an Empirical Study

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Abstract

The efficiency measures provided by DEA can be used for ranking Decision Making Units (DMU's), but this ranking cannot be applied to efficient units. Anderson and Peterson have proposed a modified efficiency measure for efficient units which can be used for ranking, but this ranking breaks down in case of units with at least one input of zero. This paper proposes an alternative efficiency measure that removes this problem. The model is illustrated by an application to the University for Teacher Education, for which the Anderson - Peterson model was not able to give a ranking for two units, which were ranked successfully by the proposed model.

(Data Envelopment Analysis, Efficiency, Ranking)

Introduction.

Development Analysis (DEA) provides a measure of the efficiency of a Decision Making Unit relative to other such units producing the outputs with the same inputs. This technique, developed by Charnes, Cooper, and Rhodes (1978), and extended by Banker, Charnes, Cooper (BCC) (1984), is a linear programming procedure for an analysis of inputs and outputs. The procedure does not require prior weights on inputs and outputs.

The standard DEA method assigns an efficiency score less than one to inefficient DMU's, from which a ranking can be derived. However, efficient DMU's have an efficiency of 1, so that for these units no ranking can be given. A model for ranking efficient units was proposed by Andersen and Petersen (1993). Their model was called Extended-DEA, and is used in this study for the University for Teacher Education (UTE). However, this model breaks down inefficient units with at least one zero input.

In this paper, a new definition of efficiency is proposed that can be extended for ranking efficient units. The extended method is applied to data for UTE.

The role of zeros in data has been considered by Cooper and Thrall (1991) and Thompson, Darnaphala, and Thrall (1993) but this paper deals with the problem of ranking the efficient units involving zeros in input data.

The paper unfolds as follows. Section 2 represents the Andersen and Petersen model. Section 3 presents a model based on a definition of efficiency in production possibility set (PPS). In section 4, the two models are compared, using two illustrative examples. Section 5 applies the two models to the UTE data. A summary is given in section 6.

2 The Andersen-Petersen Model.

The standard DEA method assigns an efficiency score of less than one to inefficient units. A score less than one means that a linear combination of the other units could produce at least the same vector of output using a smaller vector of inputs. This score can be used to rank inefficient units. Andersen and Petersen (1993) developed a similar model for ranking efficient DMU's, which in the standard DEA method have a score of 1. The basic idea in their model is to compare the unit under evaluation with a linear combination of all other units, i.e., all units excluding the unit itself. In this case, an efficiency score above 1 is obtained for efficient units. This score reflects the radial distance from the unit under evaluation to the production frontier estimated with the exclusion of that unit, i.e., the maximum proportional increase in inputs producing at least the same outputs.

The Andersen-Petersen model (AP-Model) is identical with the CCR method, except that the unit under evaluation is not included in the combination. Therefore the p^{th} DMU can be evaluated as follows:

$$r_p^* = \min r_p - \epsilon \left[\sum_{i=1}^m s_i + \sum_{r=1}^s s'_r \right]$$

subject to:

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j X_{ij} + s_i = r_p X_{ip}, \quad i = 1, \dots, m,$$

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j Y_{rj} - s'_r = Y_{rp}, \quad r = 1, \dots, s,$$

$$\lambda_j, s_i, s'_r \geq 0, \quad \forall j, i, r,$$

where Y_{rj} is the r^{th} output and X_{ij} is the i^{th} input for the j^{th} DMU, r_p is a scalar defining the share of p^{th} DMU input vector which is required in order to produce the output vector of p^{th} DMU, λ_j denotes the intensity of the j^{th} DMU, and ϵ is a non-Archimedean infinitesimal.

3 Efficiency Analysis by an Alternative Measure.

There are n DMU's to be evaluated, each consumes varying amounts of m different inputs to produce s different outputs.

In the model formulation, X_p and Y_p denote, respectively, the nonnegative vectors of input and output values for DMU _{p} .

Definition. The *production possibility set* (PPS) T is the set $\{(X_t, Y_t) | \text{the outputs } Y_t \text{ can be produced with the inputs } X_t\}$.

The set of n DMU's of actual production possibility (X_j, Y_j) , $j = 1, \dots, n$ is considered. Our focus is on the empirically defined production possibility set T with constant returns assumption that is specified by the following four postulates:

- **Postulate 1 (Ray Unboundedness).** If $(X_t, Y_t) \in T$ then $(\lambda X_t, \lambda Y_t) \in T$ for all $\lambda \geq 0$.
- **Postulate 2 (Convexity).** If $(X_t, Y_t) \in T$ and $(X_u, Y_u) \in T$, then $(\lambda X_t + (1 - \lambda)X_u, \lambda Y_t + (1 - \lambda)Y_u) \in T$ for all $\lambda \in [0, 1]$.
- **Postulate 3 (Monotonicity).** If $(X_t, Y_t) \in T$ and $X_u \geq X_t, Y_u \leq Y_t$ then $(X_u, Y_u) \in T$.
- **Postulate 4 (Inclusion of Observations).** The observed $(X_j, Y_j) \in T$ for all $j = 1, \dots, n$.
- **Postulate 5 (Minimum extrapolation).** If a production possibility set T' satisfies Postulates 1, 2, 3, and 4 then $T \subset T'$.

The unique production possibility set with constant returns assumption determined by the above postulates is given by:

$$T = \{(X_t, Y_t) | X_t \geq \sum_{j=1}^n \lambda_j X_j, Y_t \leq \sum_{j=1}^n \lambda_j Y_j, \lambda_j \geq 0, j = 1, \dots, n\}.$$

The boundary of this convex set consists of a straight line, plane, or hyperplane through the origin, as T is a convex cone that contains all of DMU's, see Figure 1 for the simplest case of single input and single output.

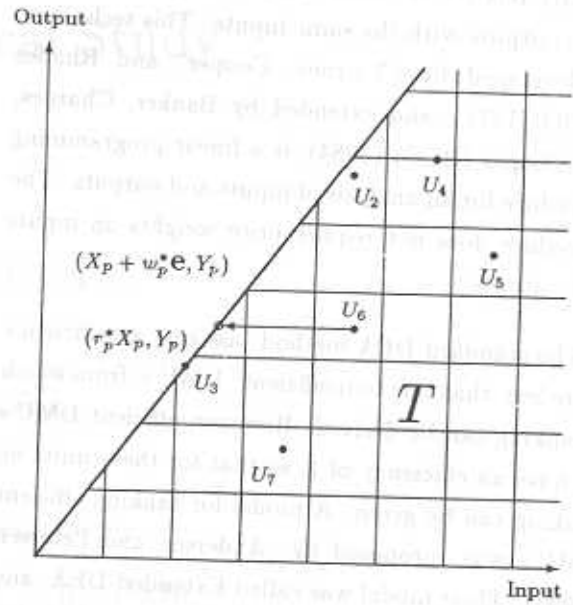


Figure 1: Production Possibility Set.

For efficiency evaluation relative to the set T , we have the following two linear programming problems:

$$\begin{array}{ll} r_p^* = \min r_p & w_p^* = \min w_p \\ \text{subject to:} & \text{subject to:} \\ (r_p X_p, Y_p) \in T, & (X_p + w_p e, Y_p) \in T, \end{array}$$

which give the **CCR-Model** and our formulation respectively as follows:

$$\begin{array}{l} r_p^* = \min r_p \\ \text{subject to:} \\ \sum_{j=1}^n \lambda_j X_j \leq r_p X_p, \\ \sum_{j=1}^n \lambda_j Y_j \geq Y_p, \\ \lambda_j \geq 0, j = 1, \dots, n, \end{array}$$

$$w_p^* = \min w_p$$

subject to :

$$\sum_{j=1}^n \lambda_j X_j \leq X_p + w_p e,$$

$$\sum_{j=1}^n \lambda_j Y_j \geq Y_p,$$

$$\lambda_j \geq 0, \quad j = 1, \dots, n,$$

e is a vector of units.

The new model assigns negative efficiency scores to inefficient units, and zero efficiency scores to all efficient units. An extension of this model can be used for ranking efficient units. This extension is identical with the model except that the unit under consideration is excluded. The extended model is as follows:

$$w_p^* = \min w_p$$

subject to :

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j X_j \leq X_p + w_p e,$$

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j Y_j \geq Y_p,$$

$$\lambda_j \geq 0, \quad j = 1, \dots, n,$$

This model leads to the non-Archimedian infinitesimal from the AP-Model as follows (this formulation will be referred to as the JAM-Model¹ in this paper):

$$w_p^* = \min w_p - \epsilon \left[\sum_{i=1}^m s_i + \sum_{r=1}^s s'_r \right]$$

subject to :

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j X_{ij} + s_i = X_{ip} + w_p, \quad i = 1, \dots, m,$$

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j Y_{rj} - s'_r = Y_{rp}, \quad r = 1, \dots, s,$$

$$\lambda_j, s_i, s'_r \geq 0, \quad \forall j, i, r.$$

Inefficient units will have a nonnegative efficiency score, while efficient units will have the same negative efficiency scores as before. Therefore, JAM-Model can be used for ranking both inefficient and efficient units. It should be obvious that the objective function values for JAM-Model are

¹ Hashemzadeh, Alirezaee and Mehrabian Model.

dependent upon the units of measurement of input data, $X_j, j = 1, \dots, n$. However, it is possible to obtain unit independence by normalization, as discussed later.

The unique production possibility set with variable returns assumption determined by postulates 2, 3, 4, and 5 is given by :

$$T = \{(X_i, Y_i) \mid X_i \geq \sum_{j=1}^n \lambda_j X_j, Y_i \leq \sum_{j=1}^n \lambda_j Y_j, \\ \sum_{j=1}^n \lambda_j = 1, \lambda_j \geq 0, \quad j = 1, \dots, n\}.$$

A discussion similar to the constant returns assumption leads to the BCC-Model and our second formulation, and extension of our second formulation for ranking efficient units can be as follows:

$$z_p^* = \min z_p - \epsilon \left[\sum_{i=1}^m s_i + \sum_{r=1}^s s'_r \right]$$

subject to :

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j X_{ij} + s_i = X_{ip} + z_p, \quad i = 1, \dots, m,$$

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j Y_{rj} - s'_r = Y_{rp}, \quad r = 1, \dots, s,$$

$$\sum_{\substack{j=1 \\ j \neq p}}^n \lambda_j = 1,$$

$$\lambda_j, s_i, s'_r \geq 0, \quad \forall j, i, r.$$

4 The Comparison of the Two Models.

Two models for ranking the efficient DMU's were discussed in section 2 and 3. Section 2 represented the AP-Model and section 3 represented the JAM-Model. This section compares these two models using two illustrative examples.

In an actual set of data, it is possible that one or more of the data inputs and outputs are zero. It is also possible that some data inputs and outputs are small in comparison with other inputs and outputs. In these cases, AP-Model, can not correctly evaluate

the efficiency of the DMU's. If the DMU under evaluation has at least one input equal to zero, the AP-Model will be infeasible and if the DMU has at least one input which is small in comparison with other inputs, AP-Model will measure this DMU without stability.

The measure given by JAM-Model successfully evaluates the above cases, so that meaningful scores are obtained for all data.

In order to make usual scores, the scores in JAM-Model may be rescaled from $[-1, +1]$ to $[0\%, 200\%]$ so that of 0 is rescaled to 100%. A score less than 100% means that the corresponding DMU is inefficient and greater than or equal to 100% means that the corresponding DMU is efficient.

4.1 Illustrative Example 1:

Table 1 gives an example of the above cases.

	A_1	A_2	A_3	B	C	D	E
input1	2	0	.1	5	10	10	2
input2	8	8	8	5	4	6	12
output1	1	1	1	1	2	2	1
output2	2	2	2	1	1	1	2

Table 1: Comparison Test Data.

There are 5 DMU's (A, B, C, D and E) each consume two inputs to produce two outputs with constant returns assumption. In order to remove the effects of changes in units of measurement from the input data, the data must be normalized before applying the method. It can be done by dividing inputs data by the maximum input (for each input).

In this example DMU_{A_1} , DMU_{A_2} and DMU_{A_3} are compared with all other DMU's (B, C, D and E) in the following three paragraphs by CCR-Model, AP-Model and JAM-Model.

- DMU_{A_1} is evaluated to be efficient by CCR-Model, and is evaluated as efficient by AP-Model with efficiency score equal to 147%. It is evaluated as efficient by JAM-Model with efficiency score equal to +0.276, which rescales to $100(1 + 0.276) = 127.6\%$. In this case, there is no problem.
- Consider now DMU_{A_2} , which has an input equal to zero. DMU_{A_2} is evaluated to be efficient by CCR-Model, but it can not be evaluated by AP-Model. However, it is evaluated as efficient by JAM-Model with efficiency score equal to +0.310 which rescales to 131.0%.
- Consider now DMU_{A_3} , which has an input equal to 0.1: DMU_{A_3} is evaluated as efficient by CCR-Model, and can be evaluated as efficient by AP-Model with efficiency score equal to 2000% which is unstable. It is evaluated as efficient by JAM-Model with efficiency score equal to +0.309 which rescales to 130.9%.

4.2 Illustrative Example 2:

A comparison of these two procedures for ranking DMU's is illustrated on the Farrell frontier. Consider the DMU's of Figure 2, each produces one output using two inputs with constant returns assumption. DMU_C is efficient and it can be evaluated by AP-Model with efficiency score of $(100 \frac{OC'}{OC})$ and evaluated by JAM-Model with efficiency score w_C^* which rescales to $100(1 + w_C^*)$.

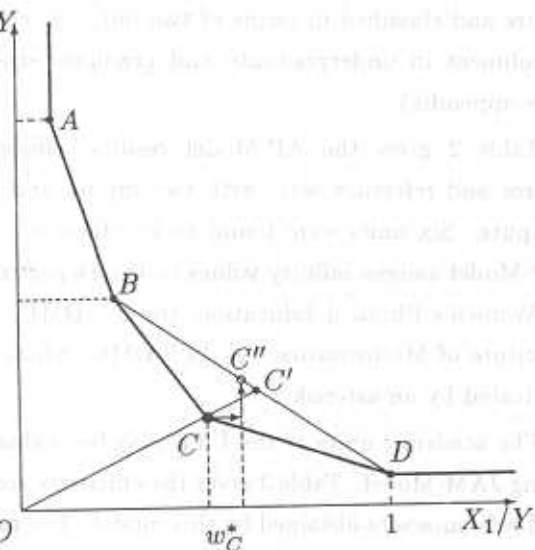


Figure 2: Farrell Efficiency Measurements.

Some examples are presented in the following figures that show the AP-Model cannot evaluate the efficiencies of some DMU's correctly.

DMU_A has zero for input 1 (see Figure 3):

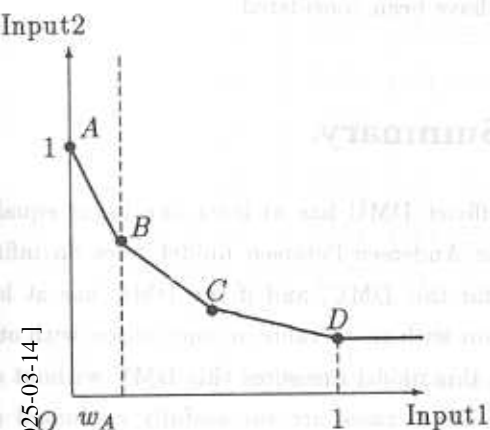


Figure 3: DMU_A has zero for input 1.

In this figure AP-Model evaluates DMU_A with efficiency score of $100 \frac{OA'}{OA} \%$ that is ∞ but this DMU is evaluated with efficiency score of $100(1 + w_A) \%$ by JAM-Model.

• DMU_A has small value for input 1 (see Figure 4):

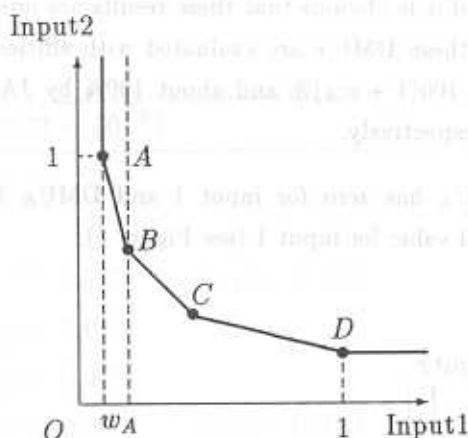


Figure 4: DMU_A has small value for input 1.

In this figure, AP-Model evaluates DMU_A with efficiency score of $(100 \frac{OA'}{OA}) \%$ that is much greater than 100%, where is unstable, but this DMU is evaluated with efficiency score of $100(1 + w_A) \%$ by JAM-Model.

• DMU_A and DMU_B are similar units that have small values for input 1 (see Figure 5):

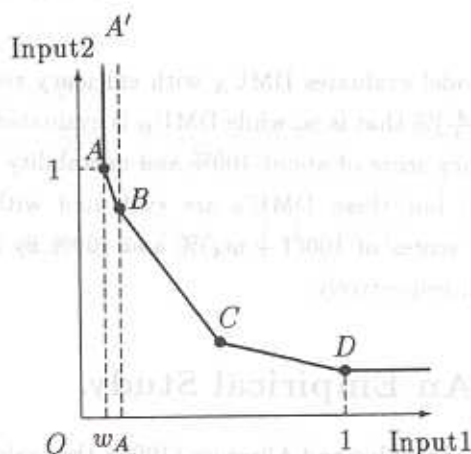


Figure 5: DMU_A and DMU_B are similar with small values for input 1.

In this figure, AP-Model evaluates DMU_A with efficiency score of much greater than 100%, while DMU_B is evaluated with efficiency score of about 100%, and it is obvious that these results are unstable, but these DMU's are evaluated with efficiency scores of $100(1 + w_A)\%$ and about 100% by JAM-Model, respectively.

- DMU_A has zero for input 1 and DMU_B has small value for input 1 (see Figure 6):

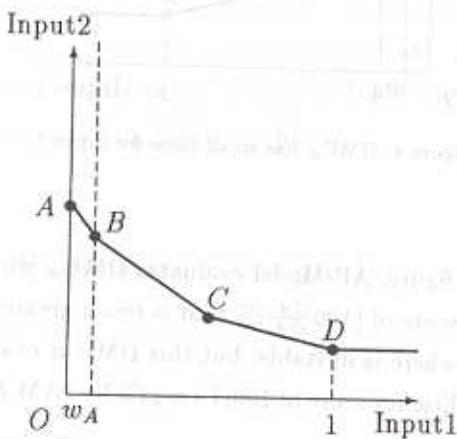


Figure 6: DMU_A has zero for input 1 and DMU_B has small value for input 1.

AP-Model evaluates DMU_A with efficiency score of $(100 \frac{O A'}{O A})\%$ that is ∞ while DMU_B is evaluated with efficiency score of about 100% and instability is observed, but these DMU's are evaluated with efficiency scores of $100(1 + w_A)\%$ and 100% by JAM-Model, respectively.

5 An Empirical Study.

In Jahanshahloo and Alirezaee (1995), the evaluation of teaching in the UTE was considered. Teaching inputs were expressed in teacher hours and classified in terms of two inputs, professorial staff and instructors. Teaching outputs were expressed in student

hours and classified in terms of two outputs, course enrollment in undergraduate and graduate studies (see appendix).

Table 2 gives the AP-Model results, efficiency scores and reference sets, with two inputs and two outputs. Six units were found to be efficient. The AP-Model assigns infinity values to the Department of Women's Physical Education, the 9th DMU, and Institute of Mathematics, the 19th DMU, which are indicated by an asterisk.

The academic units at the UTE may be evaluated using JAM-Model. Table 3 gives the efficiency scores and reference sets obtained by this model. The ranking is approximately the same as that of Table 2, except that DMU's 9 and 19 now have an explicit ranking.

Extended model, JAM-Model, successfully evaluated all efficient academic units at the UTE, in contrast to AP-Model.

In the application of AP-Model and JAM-Model on real data-set of the UTE, computational DEA issues of Ali (1994), Ali (1993), and Ali and Seiford (1993) have been considered.

6 Summary.

If an efficient DMU has at least one input equal to zero the Andersen-Petersen model gives an infinite result for this DMU, and if the DMU has at least one input with small value in comparison with other inputs, this model measures this DMU without stability. These cases are successfully evaluated and ranked by the new model proposed in this paper.

Computational difficulties of the Andersen-Petersen model were observed in evaluating efficient academic units at the UTE. This model could not evaluate the Department of Women's Physical Education and the Institute of Mathematics. These academic units were successfully evaluated by the new model.

DMU	Eff.	Ref. Sets ($\epsilon = 0.33 \times 10^{-6}$)		
9	*			
19	*			
2	174%	$\lambda_2 = 0.492$	$\lambda_7 = 1.173$	$\lambda_{10} = 0.114$
15	133%	$\lambda_1 = 0.938$	$\lambda_{19} = 2.064$	
5	130%	$\lambda_8 = 0.956$	$\lambda_{19} = 0.479$	
1	115%	$\lambda_2 = 0.492$	$\lambda_{10} = 0.220$	$\lambda_{15} = 0.353$
8	97%	$\lambda_2 = 0.276$	$\lambda_5 = 0.648$	$\lambda_9 = 0.641$
10	96%	$\lambda_1 = 1.060$	$\lambda_2 = 0.603$	
3	95%	$\lambda_1 = 0.585$	$\lambda_2 = 0.073$	
17	89%	$\lambda_2 = 0.375$	$\lambda_5 = 0.091$	$\lambda_{19} = 0.338$
18	85%	$\lambda_2 = 0.978$	$\lambda_5 = 0.191$	$\lambda_{19} = 0.186$
7	71%	$\lambda_2 = 0.487$	$\lambda_9 = 0.204$	
12	66%	$\lambda_1 = 0.564$	$\lambda_2 = 0.285$	$\lambda_{19} = 0.392$
4	63%	$\lambda_1 = 0.542$	$\lambda_2 = 0.156$	
6	58%	$\lambda_1 = 0.131$	$\lambda_2 = 0.274$	
16	57%	$\lambda_1 = 0.231$	$\lambda_2 = 0.582$	
14	54%	$\lambda_1 = 0.726$	$\lambda_2 = 0.232$	
13	45%	$\lambda_1 = 1.210$	$\lambda_2 = 0.099$	
11	45%	$\lambda_1 = 0.048$	$\lambda_2 = 0.528$	$\lambda_{19} = 0.504$

Table 2: AP-Model Efficiency Scores for 19 Academic Units of the UTE.

DMU	Eff.	Rescaled	Ref. Sets $(\epsilon = 0.55 \times 10^{-6})$		
19	+0.281	128%	$\lambda_{15} = 0.579$	$\lambda_{17} = 0.850$	$\lambda_{19} = 0.094$
5	+0.104	110%	$\lambda_2 = 0.033$	$\lambda_8 = 0.831$	$\lambda_{19} = 0.580$
2	+0.092	109%	$\lambda_2 = 0.575$	$\lambda_7 = 0.647$	$\lambda_{10} = 0.274$
15	+0.065	106%	$\lambda_1 = 0.938$	$\lambda_{19} = 1.491$	
1	+0.047	105%	$\lambda_2 = 0.575$	$\lambda_{10} = 0.177$	$\lambda_{15} = 0.358$
9	+0.043	104%	$\lambda_2 = 0.789$	$\lambda_9 = 0.701$	
8	-0.010	99%	$\lambda_2 = 0.228$	$\lambda_5 = 0.648$	$\lambda_9 = 0.701$
3	-0.011	99%	$\lambda_1 = 0.590$	$\lambda_2 = 0.066$	
7	-0.020	98%	$\lambda_2 = 0.310$	$\lambda_9 = 0.428$	
10	-0.021	98%	$\lambda_1 = 1.055$	$\lambda_2 = 0.609$	
17	-0.022	98%	$\lambda_2 = 0.376$	$\lambda_5 = 0.091$	$\lambda_{19} = 0.338$
18	-0.051	95%	$\lambda_2 = 0.870$	$\lambda_5 = 0.265$	$\lambda_{19} = 0.094$
6	-0.070	93%	$\lambda_1 = 0.044$	$\lambda_2 = 0.398$	
4	-0.118	88%	$\lambda_1 = 0.561$	$\lambda_2 = 0.128$	
16	-0.141	86%	$\lambda_1 = 0.007$	$\lambda_2 = 0.903$	$\lambda_{19} = 0.029$
12	-0.153	85%	$\lambda_1 = 0.717$	$\lambda_{15} = 0.049$	$\lambda_{19} = 0.278$
14	-0.235	77%	$\lambda_1 = 0.752$	$\lambda_2 = 0.194$	
11	-0.250	75%	$\lambda_1 = 0.379$	$\lambda_2 = 0.054$	$\lambda_{19} = 0.371$
13	-0.457	54%	$\lambda_1 = 1.151$	$\lambda_{15} = 0.137$	

Table 3: JAM-Model Efficiency Scores for 19 Academic Units of the UTE.

ent. Useful comments from Dr. [Name], Professor of Economics, the University of Canada, Dr. R. M. Thrall, Professor of Administration Jones Graduate School of Administration and Noah Harding Professor of Mathematical Sciences, Rice University. One anonymous referee are gratefully

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No.	Department/Institute	I1	I2	O1	O2
Faculty of Literature					
1	Persian Literature	81.0	87.6	5191	205
2	Theology and Islamic Culture	85.0	12.8	3629	0
3	History	56.7	55.2	3302	0
4	Geography	91.0	78.8	3379	8
5	Foreign Languages	216.0	72.0	5368	639
6	Arabic Language and Literature	58.0	25.6	1674	0
7	Social Sciences	112.2	8.8	2350	0
Faculty of Physical Ed.					
8	Men Physical Education	293.2	52.0	6315	414
9	Women Physical Education	186.6	0.0	2865	0
Faculty of Sciences					
10	Mathematics	143.4	105.2	7689	66
11	Geology	108.7	127.0	2165	266
12	Biology	105.7	134.4	3963	315
13	Chemistry	235.0	236.8	6643	236
14	Physics	146.3	124.0	4611	128
Faculty of Education					
15	Foundations of Education	57.0	203.0	4869	540
16	Instructional Technology	118.7	48.2	3313	16
17	Psychology	58.0	47.4	1853	230
18	Guidance and Counseling	146.0	50.8	4578	217
19	Institute of Mathematics	0.0	91.3	0	508

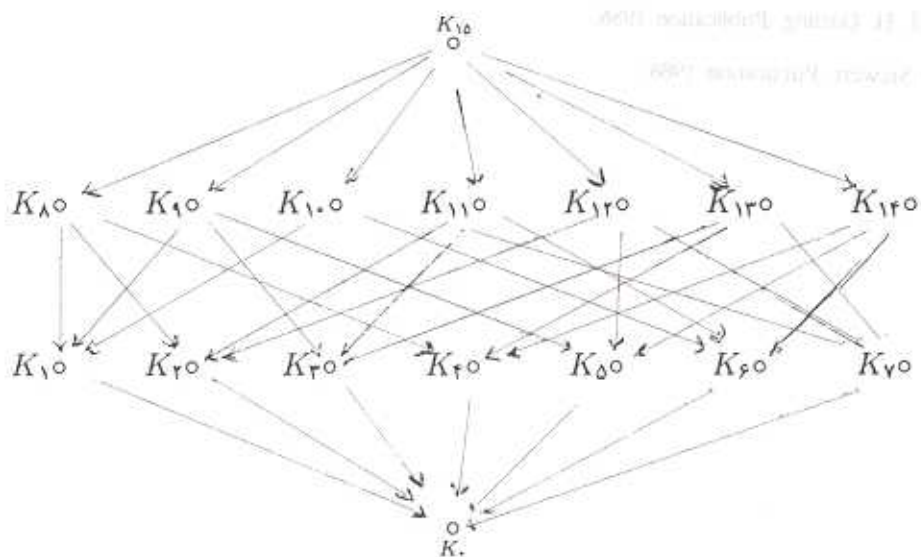
APPENDIX: Inputs and Outputs for 19 Academic Units of the UTE
in the First Semester, 1993-94.

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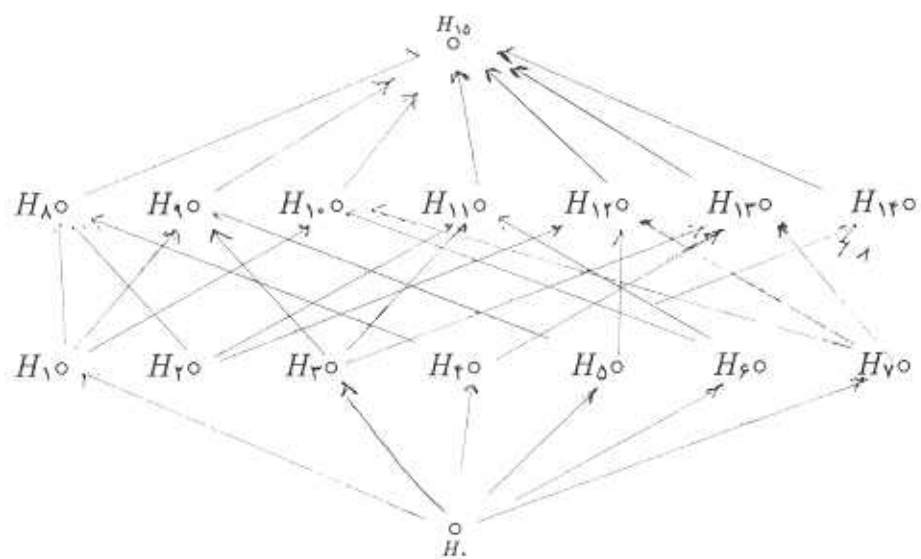
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شبکه زیر میدانهای $\mathbb{Q}(\sqrt{p}, \sqrt{q}, \sqrt{t})$



شبکه زیر گروه‌های $\text{Gal}_{\mathbb{Q}}(f)$

برهان: بنابر بحث‌های قبل از قضیه ۴ اگر $\gamma = \sqrt{p} + \sqrt{q} + \sqrt{t}$ آنگاه $Q(\gamma) = Q(\sqrt{p}, \sqrt{q}, \sqrt{t})$ و در نتیجه چندجمله‌ای مینیمال γ روی Q از درجه ۸ می‌باشد. لذا اگر $h(x) \in Q[x]$ چندجمله‌ای ناصفر باشد به قسمی که $h(\gamma) = 0$ آنگاه $\deg(h(x)) \geq 8$.

$$\gamma = \sqrt{p} + \sqrt{q} + \sqrt{t},$$

$$\gamma - \sqrt{p} = \sqrt{q} + \sqrt{t},$$

$$\gamma^2 + p - 2\gamma\sqrt{p} = q + t + 2\sqrt{qt},$$

$$(\gamma^2 + p - q - t)^2 = 4(\gamma\sqrt{p} + \sqrt{qt})^2,$$

$$\gamma^4 + 2(p - q - t)\gamma^2 + (p - q - t)^2 = 4(\gamma^2 p + qt + 2\gamma\sqrt{pq}),$$

$$\gamma^4 - 2(p + q + t)\gamma^2 + (p^2 + q^2 + t^2 - 2pt - 2pq - 2qt) = 8\gamma\sqrt{pqt}.$$

$$\gamma^8 - 4(p + q + t)\gamma^6 + [2(p^2 + q^2 + t^2 - 2pq - 2pt - 2qt) + 4(p + q + t)^2]\gamma^4$$

$$- [4(p + q + t)(p^2 + q^2 + t^2 - 2pq - 2pt - 2qt) + 64pqt]\gamma^2$$

$$+ (p^2 + q^2 + t^2 - 2pq - 2pt - 2qt) = 0.$$

بنابراین γ صفر $f(x)$ است. از این که چندجمله‌ای مینیمال γ روی Q از درجه ۸ می‌باشد نتیجه می‌شود که روی Q تحویل‌ناپذیر است. چه در غیراین صورت γ صفر یک چندجمله‌ای از درجه کوچکتر از ۸ می‌باشد که غیر است. ▲

با فرض $K_i = \phi(H_i)$, $(0 \leq i \leq 15)$ خواهیم داشت

$$K_0 = Q(\sqrt{p}, \sqrt{q}, \sqrt{t}), K_1 = Q(\sqrt{q}, \sqrt{t}), K_2 = Q(\sqrt{p}, \sqrt{t}), K_3 = Q(\sqrt{p}, \sqrt{q})$$

$$K_4 = Q(\sqrt{t}, \sqrt{pq}), K_5 = Q(\sqrt{q}, \sqrt{pt}), K_6 = Q(\sqrt{p}, \sqrt{qt}), K_7 = Q(\sqrt{pq}, \sqrt{pt}, \sqrt{qt}),$$

$$K_8 = Q(\sqrt{t}), K_9 = Q(\sqrt{q}), K_{10} = Q(\sqrt{qt}), K_{11} = Q(\sqrt{p}), K_{12} = Q(\sqrt{pt})$$

$$K_{13} = Q(\sqrt{pq}), K_{14} = Q(\sqrt{pqt}), K_{15} = Q.$$

در صفحه بعد شبکه زیرگروه‌های $\text{Gal}_Q(f)$ و شبکه زیرمیدانهای $Q(\sqrt{p}, \sqrt{q}, \sqrt{t})$ را جهت مقایسه نشان می‌دهد.

$$[Q(\sqrt{p}, \sqrt{q}, \sqrt{t}) : Q] = |\text{Gal}_{\mathbb{Q}}(f)| = 8.$$

لذا $\text{Gal}_{\mathbb{Q}}(f)$ دارای ۱۶ زیرگروه به شرح زیر است:

$$\begin{aligned} H_0 &= \{\sigma_0\}, H_1 = \{\sigma_0, \sigma_1\}, H_2 = \{\sigma_0, \sigma_2\}, H_3 = \{\sigma_0, \sigma_3\}, H_4 = \{\sigma_0, \sigma_4\} \\ H_5 &= \{\sigma_0, \sigma_5\}, H_6 = \{\sigma_0, \sigma_6\}, H_7 = \{\sigma_0, \sigma_7\}, H_8 = \{\sigma_0, \sigma_1, \sigma_2, \sigma_4\} \\ H_9 &= \{\sigma_0, \sigma_1, \sigma_3, \sigma_5\}, H_{10} = \{\sigma_0, \sigma_1, \sigma_6, \sigma_7\}, H_{11} = \{\sigma_0, \sigma_2, \sigma_3, \sigma_6\}, \\ H_{12} &= \{\sigma_0, \sigma_2, \sigma_5, \sigma_7\}, H_{13} = \{\sigma_0, \sigma_3, \sigma_4, \sigma_7\}, H_{14} = \{\sigma_0, \sigma_4, \sigma_5, \sigma_6\}, \\ H_{15} &= \text{Gal}_{\mathbb{Q}}(f). \end{aligned}$$

فرض کنید $B = \{K | Q \leq K \leq Q(\sqrt{p}, \sqrt{q}, \sqrt{t})\}$ و $A = \{H_i | 0 \leq i \leq 15\}$

$$\psi : A \rightarrow B.$$

$$H_i \rightsquigarrow \phi(H_i)$$

و a, b, c اعداد گویای ناصفری باشند و $\alpha = a\sqrt{p} + b\sqrt{q} + c\sqrt{t}$. در این صورت $Q(\alpha)$ زیرمیدانی از $Q(\sqrt{p}, \sqrt{q}, \sqrt{t})$ است و برای هر $(1 \leq i \leq 15)$ ، $\alpha \notin \phi(H_i)$ ، زیرا برای هر چنین i زیرگروه H_i عضوی دارد که α را روی خودش تصویر نمی‌کند. بنابراین $(1 \leq i \leq 15)$ ، $Q(\alpha) \neq \phi(H_i)$ و در نتیجه $Q(\alpha) = Q(\sqrt{p}, \sqrt{q}, \sqrt{t})$. لذا

$$[Q(\alpha) : Q] = [Q(\sqrt{p}, \sqrt{q}, \sqrt{t}) : Q] = 8.$$

بنابراین چند جمله‌ای مینیمال α روی Q از درجه ۸ می‌باشد، در نتیجه اگر $g(x) \in Q[x]$ یک چند جمله‌ای ناصفر باشد به قسمی که $g(\alpha) = 0$ آنگاه $\deg(g(x)) \geq 8$.

قضیه ۴: اگر p, q, t سه عدد اول دویبه‌دو متمایز باشند آنگاه

$$\begin{aligned} f(x) &= x^8 - 2(p+q+t)x^6 + 2[(p+q+t)^2 + 2(p^2+q^2+t^2)]x^4 \\ &\quad - 2[(p+q+t)(p^2+q^2+t^2) - 2pq - 2pt - 2qt]x^2 \\ &\quad + (p^2+q^2+t^2 - 2pq - 2pt - 2qt)^2. \end{aligned}$$

روی Q تحویل‌ناپذیر است.

برهان: $Q(i, \sqrt{m}) = Q(i + \sqrt{m})$: لذا

$$[Q(i + \sqrt{m}) : Q] = [Q(i, \sqrt{m}) : Q] = ۴$$

بنابراین چندجمله‌ای مینیمال $i + \sqrt{m}$ روی Q از درجه ۴ می‌باشد، در نتیجه اگر $s(x) \in Q[x]$ یک چندجمله‌ای باشد به قسمی که $s(i + \sqrt{m}) = 0$ آنگاه $\deg(s(x)) \geq ۴$. با فرض

$$\alpha = i + \sqrt{m},$$

$$\alpha^2 = -1 + m + 2i\sqrt{m},$$

$$\alpha^2 + (1 - m)^2 + 2(1 - m)\alpha^2 = -4m,$$

$$\alpha^2 + (1 - m)^2 + 2(1 - m)\alpha^2 = -4m,$$

$$\alpha^2 + 2(1 - m)\alpha^2 + (m + 1)^2 = 0$$

بنابراین α صفر چندجمله‌ای $t(x)$ می‌باشد. در نتیجه $t(x)$ روی Q تحویل‌ناپذیر است چه در غیر این صورت یک چندجمله‌ای از درجه حداکثر ۳ می‌باشد که غیرممکن است. \blacktriangle

فرض کنید p, q, t سه عدد اول دویبه‌دو متمایز باشند و $f = (x^2 - p)(x^2 - q)(x^2 - t)$ در $Q(\sqrt{p}, \sqrt{q}, \sqrt{t})/Q$ توسیع میدان تجزیه‌ای f روی Q است.

$$\sqrt{p}, \sqrt{q}, \sqrt{t} = \{a + b_1\sqrt{p} + b_2\sqrt{q} + b_3\sqrt{t} + c_1\sqrt{pq} + c_2\sqrt{pt} + c_3\sqrt{qt} + d\sqrt{pqt} | a, b_i, c_i, d \in Q\},$$

$$\text{Gal}_Q(f) = \{\sigma_0, \sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6, \sigma_7\}.$$

اگر $\sigma \in \text{Gal}_Q(f)$ آنگاه برای هر $q \in Q$ داریم $\sigma(q) = q$. لذا برای مشخص کردن یک σ کافی است $\sigma : Q(\sqrt{p}, \sqrt{q}, \sqrt{t}) \rightarrow Q(\sqrt{p}, \sqrt{q}, \sqrt{t})$ را معین کنیم.

نتیجه می‌شود که $\sigma(\sqrt{t}) = \pm\sqrt{t}$ و $\sigma(\sqrt{q}) = \pm\sqrt{q}$ و $\sigma(\sqrt{p}) = \pm\sqrt{p}$.

$$\begin{matrix} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \\ \sqrt{t} \rightarrow \sqrt{t} \end{matrix}, \sigma_1 : \begin{cases} \sqrt{p} \rightarrow -\sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \\ \sqrt{t} \rightarrow \sqrt{t} \end{cases}, \sigma_2 : \begin{cases} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow -\sqrt{q} \\ \sqrt{t} \rightarrow \sqrt{t} \end{cases}, \sigma_3 : \begin{cases} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \\ \sqrt{t} \rightarrow -\sqrt{t} \end{cases}$$

$$\begin{matrix} \sqrt{p} \rightarrow -\sqrt{p} \\ \sqrt{q} \rightarrow -\sqrt{q} \\ \sqrt{t} \rightarrow \sqrt{t} \end{matrix}, \sigma_4 : \begin{cases} \sqrt{p} \rightarrow -\sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \\ \sqrt{t} \rightarrow -\sqrt{t} \end{cases}, \sigma_5 : \begin{cases} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow -\sqrt{q} \\ \sqrt{t} \rightarrow -\sqrt{t} \end{matrix}, \sigma_6 : \begin{cases} \sqrt{p} \rightarrow -\sqrt{p} \\ \sqrt{q} \rightarrow -\sqrt{q} \\ \sqrt{t} \rightarrow -\sqrt{t} \end{matrix}, \sigma_7 : \begin{cases} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \\ \sqrt{t} \rightarrow \sqrt{t} \end{cases}$$

برهان: چون α به هیچیک از زیرمیدانهای $Q(\sqrt{p})$ ، $Q(\sqrt{q})$ ، $Q(\sqrt{pq})$ و Q تعلق ندارد، و $Q(\alpha)$ زیرمیدانی از

$$\Delta. Q(\alpha) = Q(\sqrt{p}, \sqrt{q}) \text{ است که با هیچیک از این چهار زیرمیدان برابر نیست پس } Q(\alpha) = Q(\sqrt{p}, \sqrt{q}).$$

قضیه ۲: اگر q, p دو عدد صحیح و مثبت و خالی از مربع باشند به قسمی که λq و λp و q و a, b اعداد گویای ناصفر باشند آنگاه چندجمله‌ای $f(x) = x^4 - 2(a^2p + b^2q)x^2 + (a^2p - b^2q)^2$ روی Q تحویل‌ناپذیر است.

برهان: با فرض $\alpha = a\sqrt{p} + b\sqrt{q}$ بنابر لم یک داریم $Q(\alpha) = Q(\sqrt{p}, \sqrt{q})$. بنابراین $[Q(\alpha) : Q] = [Q(\sqrt{p}, \sqrt{q}) : Q] = 4$ در نتیجه چندجمله‌ای مینیمال α روی Q از درجه ۴ می‌باشد. لذا اگر $g(x) \in Q[x]$ یک چندجمله‌ای ناصفر باشد به قسمی که

$$\deg(g(x)) \geq 2 \quad g(\alpha) = 0 \quad \text{آنگاه} \quad (2)$$

$$\alpha = a\sqrt{p} + b\sqrt{q}.$$

$$\alpha^2 = a^2p + b^2q + 2ab\sqrt{pq}.$$

$$\alpha^2 - (a^2p + b^2q) = 2ab\sqrt{pq}.$$

$$\alpha^4 + (a^2p + b^2q)^2 - 2(a^2p + b^2q)\alpha^2 = 4a^2b^2pq,$$

$$\alpha^4 - 2(a^2p + b^2q)\alpha^2 + (a^2p - b^2q)^2 = 0.$$

بنابراین α صفر $f(x)$ می‌باشد. از این که چندجمله‌ای مینیمال α در Q از درجه ۴ می‌باشد نتیجه می‌شود که $f(x)$ روی Q تحویل‌ناپذیر است. چه در غیر این صورت α صفریک چندجمله‌ای از درجه کوچکتر از ۴ روی Q می‌باشد که با (۲) تناقض دارد. Δ

نتیجه یک: اگر q, p دو عدد خالی از مربع باشند به قسمی که λq و λp و q و a آنگاه چندجمله‌ای $g(x) = x^2 - 2(p+q)x^2 + (p-q)^2$ روی Q تحویل‌ناپذیر است.

برهان: با قراردادن $a = b = 1$ در قضیه ۲ نتیجه حاصل می‌شود. Δ

نتیجه ۲: اگر q, p دو عدد طبیعی خالی از مربع باشند به قسمی که λq و λp و q و a یک عدد گویای ناصفر باشد آنگاه چندجمله‌ای $h(x) = x^2 - 2(p+q)a^2x^2 + a^4(p-q)^2$ روی Q تحویل‌ناپذیر است.

برهان: با قراردادن $a = b$ در قضیه ۲ نتیجه حاصل می‌شود. Δ

قضیه ۳: اگر m عددی صحیح و مثبت و مربع کامل نباشد (یعنی عددی اول چون p وجود دارد که $p^k | m$ و $p^{k+1} \nmid m$) و k فرد است) آنگاه چندجمله‌ای $t(x) = x^2 - 2(m-1)x^2 + (m+1)^2$ روی Q تحویل‌ناپذیر است.

یک زیرمیدان E می باشد که شامل F است. به عکس اگر K زیرمیدانی از E و شامل F باشد، $\{\sigma \in \text{Gal}_F(f) \mid \forall k \in K (\sigma(k) = k)\}$ زیرگروهی از $\text{Gal}_F(f)$ است. چنانچه:

$$A = \{K \mid K \text{ زیرمیدانی از } E \text{ که شامل } F \text{ است}\},$$

$$B = \{H \mid H \text{ یک زیرگروه } \text{Gal}_F(f) \text{ است}\},$$

آنگاه تابع $(1) \psi: B \rightarrow A$ با ضابطه $\psi(H) = \phi(H)$ یک تناظر یک به یک است. فرض کنید p, q دو عدد خالی از مربع باشند به قسمی که $q \neq (p, q) \neq p$ و $(x^2 - p)(x^2 - q) = f$ این صورت $Q(\sqrt{p}, \sqrt{q})/Q$ یک توسیع میدان تجزیه ای f است.

$$Q(\sqrt{p}, \sqrt{q}) = \{a_0 + a_1\sqrt{p} + a_2\sqrt{q} + a_3\sqrt{pq} \mid a_i \in Q\}$$

$$|\text{Gal}_Q(f)| = [Q(\sqrt{p}, \sqrt{q}) : Q] = 4.$$

با فرض $\text{Gal}_Q(f) = \{\sigma_0, \sigma_1, \sigma_2, \sigma_3\}$ هر یک از σ_i ($0 \leq i \leq 3$) یک خودریختی روی $Q(\sqrt{p}, \sqrt{q})$ که هر عضو Q را ثابت نگه میدارند. برای مشخص کردن یک خودریختی روی $Q(\sqrt{p}, \sqrt{q})$ کافی است $\sigma(\sqrt{p})$ را معین نماییم. از آنجا که $\sigma(\sqrt{p}) = \pm\sqrt{p}$ و $\sigma(\sqrt{q}) = \pm\sqrt{q}$ نتیجه می شود که اعضای $\text{Gal}_Q(f)$ شرح زیر می باشند

$$\sigma_0: \begin{cases} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \end{cases}, \sigma_1: \begin{cases} \sqrt{p} \rightarrow -\sqrt{p} \\ \sqrt{q} \rightarrow \sqrt{q} \end{cases}, \sigma_2: \begin{cases} \sqrt{p} \rightarrow \sqrt{p} \\ \sqrt{q} \rightarrow -\sqrt{q} \end{cases}, \sigma_3: \begin{cases} \sqrt{p} \rightarrow -\sqrt{p} \\ \sqrt{q} \rightarrow -\sqrt{q} \end{cases}$$

بنابراین $\text{Gal}_Q(f)$ دارای زیرگروه های

$$H_0 = \{\sigma_0\}, \quad H_1 = \{\sigma_0, \sigma_1\}, \quad H_2 = \text{Gal}_Q(f), \quad H_3 = \{\sigma_0, \sigma_3\}, \quad H_4 = \{\sigma_0, \sigma_2\}.$$

در نتیجه زیرمیدانهای متناظر H_i ها بنابر رابطه (۱) که تمام زیرمیدانهای $Q(\sqrt{p}, \sqrt{q})$ نیز می باشند به شرح زیر می باشند

$$\phi(H_0) = Q(\sqrt{p}, \sqrt{q})$$

$$\phi(H_1) = Q, \quad \phi(H_2) = Q(\sqrt{p}), \quad \phi(H_3) = Q(\sqrt{pq}), \quad \phi(H_4) = Q(\sqrt{q})$$

لم ۱: اگر a, b اعداد گویای ناصفر و p, q دو عدد خالی از مربع باشند به قسمی که $q \neq (p, q) \neq p$ و $Q(\alpha) = Q(\sqrt{p}, \sqrt{q})$ آنگاه $\alpha = a\sqrt{p} + b\sqrt{q}$