IMMEDIATE DETERMINATION OF STANDARD FORMS FOR BOOLEAN FUNCTIONS FROM ONE TRUTH MAP

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One of the interesting and important problems in Boolean algebra is how to obtain one of the eight standard forms or reductions for logical functions. The well-known procedure is as follows [see e.g.: 9]. A truth table may supply the initial data derived from the statement of problem. Then the data from the truth table are deposited into the cells of the minterm (or the maxterm) map. From the "1's" (or the "0's") in the minterm map (or in the maxterm map) either one of the standard forms or one of the initial reductions can be obtained. From each standard form or initial reduction other three forms or reductions can be determined, successively applying De Morgan's theorem. There are altogether eight standard forms, each of which is adapted to a different physical implementation. Finding all eight reductions is often of academic interest only, although it is necessary in principle to be able to find all eight so that a particular one can be found when needed. In most cases only one or two of the standard forms or reductions is important for the practice.

The aim of this paper is to show, how a preferred standard form or reduction can *immediately* be obtained from one truth map, for example from the minterm map. Of course, if needed also the maxterm map can be taken as a basis.

1. The eight standard forms

Let it be* m_i^n a minterm of n variables. A *minterm* is defined as a *product* in which every variable (either plain: v or inverted: $\bar{v}$) appears once and only once. On the other hand, a *minterm form* of a particular logical or switching function is a *sum* of those particular minterms which describe the function in question.

For example $m_4^3 = a\,\bar{b}\,\bar{c}$ is a minterm of the three ($n = 3$) variables $a, b, c,$ and

* The upper index does not signify a power or derivation, it means the number of variables only.

$$f_1^3 = m_0^3 + m_1^3 + m_2^3 + m_3^3 + m_4^3 = \bar{a}\bar{b}\bar{c} + \bar{a}\bar{b}c + \bar{a}b\bar{c} + \bar{a}bc + a\bar{b}\bar{c} \quad (1e)$$

is a minterm form.*

Similarly, let it be M_k^n a maxterm of n variables. A *maxterm* is defined as a *sum* in which every variable (either plain or inverted) appears once and only once, while a *maxterm form* of a particular logical or switching function is a *product* of those particular maxterms which describe the function in question.

For example $M_3^3 = \bar{a} + b + c$ is a maxterm of the three variables a, b, c while

$$f_2^3 = M_7^3 M_6^3 M_5^3 M_4^3 = (a + b + c)(a + b + \bar{c})(a + \bar{b} + c)(a + \bar{b} + \bar{c})$$

is the maxterm form of another function.

Similarly, the first function can be expressed in maxterm form as

$$f_1^3 = M_0^3 M_1^3 M_2^3 = (\bar{a} + \bar{b} + \bar{c})(\bar{a} + \bar{b} + c)(\bar{a} + b + \bar{c}) \quad (7e)$$

The following relations are valid

$$\overline{m_i^n} = M_{2^n-1-i}^n$$

and

$$\overline{M_k^n} = m_{2^n-1-k}^n$$

where the subscripts i or k employed are based on assuming that all plain variables $v = a, b, c \ldots$ have the value "1" and, therefore, all inverted (complementary) variables $\bar{v} = \bar{a}, \bar{b}, \bar{c} \ldots$ have the value "0", thus each different value combination represents a binary number. This binary number converted to a decimal number gives the value of index i or k.

For example $m_4^3 = a\bar{b}\bar{c}$, because 100 as binary number indeed signifies 4. On the other hand, $M_3^3 = \bar{a} + b + c$ and 011 as binary number gives 3. Applying De Morgan's theorem, it becomes evident that undoubtedly:

$$\overline{m_4^3} = \overline{a\bar{b}\bar{c}} = \bar{a} + b + c = M_3^3$$

All the above-mentioned definitions and relations are well-known and figure here only for the sake of completeness.

A minterm form can be expressed as

* f_1^3 is a symbolic notation of the fact that f_1 is a function of three (plain or inverted) variables.

$$f^n = \sum_{i=0}^{2^n-1} a_i\, m_i^n \tag{1a}$$

where a_i has the value "1" if m_i^n figure in the function and a_i has the value "0" if m_i^n is absent.

In the above-mentioned first example $a_0 = 1$, $a_1 = 1$, $a_2 = 1$, $a_3 = 1$, $a_4 = 1$, while $a_5 = 0$, $a_6 = 0$, $a_7 = 0$.

The minterm form (1a) can symbolically also be expressed as:

$$f^n = \mathrm{O}(\mathrm{A}(\mathrm{V})) \tag{1b}$$

where A denotes an AND operation and O an OR operation, while V is a set of the n variables $v = a, b, c \ldots$, each can be plain or inverted, but figuring once and only once.

After twofold negation and applying De Morgan's theorem, we obtain:

$$f^n = \overline{\overline{\sum_{i=0}^{2^n-1} a_i\, m_i^n}} = \overline{\prod_{i=0}^{2^n-1} \overline{a_i\, m_i^n}} \tag{2a}$$

which can also be expressed as

$$f^n = \mathrm{NA}\,(\mathrm{NA}(\mathrm{V})) \tag{2b}$$

where NA denotes the so-called NAND operation, that is, the NOT AND operation.

For example, the function taken as first illustration can be expressed in the second standard form as:

$$f_1^3 = \overline{\overline{(\bar a\bar b\bar c)}\;\overline{(\bar a\bar b c)}\;\overline{(\bar a b\bar c)}\;\overline{(\bar a b c)}\;\overline{(a\bar b\bar c)}} \tag{2e}$$

Applying once more De Morgan's theorem we obtain:

$$f^n = \overline{\prod_{i=0}^{2^n-1} (\bar a_i + \overline{m_i^n})} = \overline{\prod_{i=0}^{2^n-1} (\bar a_i + M^n_{2^n-1-i})} \tag{3a}$$

or symbolically:

$$f^n = \mathrm{NA}\,(\mathrm{O}(\mathrm{NV})) \tag{3b}$$

where NA and O represent NAND and OR operation, respectively, while NV represents the complementary set of the variables v or $\bar v$ that is each of the plain variables $v = a, b, c \ldots$ or inverted variables $\bar v = \bar a, \bar b, c$ must be taken with a negation (that is inverted: $\bar{v}$ or plain: v), but of course, each variable can figure once and only once.

The illustrative function taken as example can be written in the following standard form:

$$f_1^3 = \overline{(a + b + c)\,(a + b + \bar{c})\,(a + \bar{b} + c)\,(a + \bar{b} + \bar{c})\,(\bar{a} + b + c)} \qquad (3e)$$

Finally, De Morgan's theorem gives the fourth standard form:

$$f^n = \sum_{i=0}^{2^n-1} \overline{(\bar{a}_i + M^n_{2^n-1-i})} \qquad (4a)$$

furnishing the following symbolic form:

$$f^n = \mathrm{O}(\mathrm{NO}(\mathrm{NV})) \qquad (4b)$$

where O and NO denote the OR and NOT OR or NOR operation, while NV is the complementary set of the variables (each being plain or inverted).

According to this standard form the function in question can be expressed as:

$$f_1^3 = \overline{(a + b + c)} + \overline{(a + b + \bar{c})} + \overline{(a + \bar{b} + c)} + \overline{(a + \bar{b} + \bar{c})} + \overline{(\bar{a} + b + c)} \quad (4e)$$

If we apply De Morgan's theorem once more, we again arrive back to relation (1a) and (1b), respectively. Thus, the cycle is closed.

Let us now start from the inverted minterm form, that is from:

$$f^n = \overline{\sum_{i=0}^{2^n-1} (\bar{a}_i\, m_i^n)} \qquad (5a)$$

It must be noted, that now just those minterms appear which are missing in the expression (1a). This standard form can be expressed symbolically as:

$$f^n = \mathrm{NO}\ (\mathrm{A}(\mathrm{V})) \qquad (5b)$$

These relations for the illustrative function yield:

$$f_1^3 = \overline{(a\bar{b}c) + (ab\bar{c}) + (abc)} \qquad (5e)$$

Moving in the overall negation

$$f^n = \prod_{i=0}^{2^n-1} \overline{(\bar{a}_i\, m_i^n)} \qquad (6a)$$

or symbolically:

$$f^n = \mathrm{A}(\mathrm{NA}(\mathrm{V})) \tag{6b}$$

For the example this relation yields

$$f_1^3 = \overline{(a\bar{b}c)}\ \overline{(ab\bar{c})}\ \overline{(abc)} \tag{6e}$$

Now applying De Morgan's theorem

$$f^n = \prod_{i=0}^{2^n-1} (a_i + \overline{m_i^n}) = \prod_{i=0}^{2^n-1} (a_i + M_{2^n-1-i}) \tag{7a}$$

This is a standard *maxterm* form which can also be expressed as

$$f^n = \mathrm{A}\,(\mathrm{O}(\mathrm{NV})) \tag{7b}$$

For the example we obtain the following maxterm form:

$$f_1^3 = (\bar{a} + b + \bar{c})\,(\bar{a} + \bar{b} + c)\,(\bar{a} + \bar{b} + \bar{c}) \tag{7e}$$

(This expression has already been previously given.)

Finally, assuming an overall double negation, and then moving one negation in the inside, the result is:

$$f^n = \overline{\sum_{i=0}^{2^n-1} \overline{(a_i + M_{2^n-1-i})}} \tag{8a}$$

Evidently this standard form can be denoted as

$$f^n = \mathrm{NO}\,(\mathrm{NO}(\mathrm{NV})) \tag{8b}$$

In our example

$$f_1^3 = \overline{\overline{(\bar{a} + b + \bar{c})} + \overline{(\bar{a} + \bar{b} + c)} + \overline{(\bar{a} + \bar{b} + \bar{c})}} \tag{8e}$$

The cycle is closed, because applying De Morgan's theorem again leads to Eqs. (5a) and (5b), respectively.

Figure 1/*a* illustrates the minterm truth map (Karnaugh table [3, 4]) for three variables in general and Fig. 1/*b* that of the problem investigated in simplified form, because only the values of a_i' s are demonstrated. The standard form in Eqs (1a), (1b) can be obtained from the "1's" while the form in Eqs. (5a), (5b) from the "0's" of the minterm map. As we have seen from this minterm forms (applying De Morgan's theorem) altogether eight standard forms can be obtained.

Similarly, our starting point could be a maxterm map. If the identifying process were repeated for the "0's" and "1's" of the maxterm map the same eight standard forms would be obtained, although the cycles would be entered at different points.

	$\bar{b}$	$\bar{b}$	b	b
$\bar{a}$	$\alpha_0 m_0^3$	$\alpha_1 m_1^3$	$\alpha_3 m_3^3$	$\alpha_2 m_2^3$
a	$\alpha_4 m_4^3$	$\alpha_5 m_5^3$	$\alpha_7 m_7^3$	$\alpha_6 m_6^3$
	$\bar{c}$	c	c	$\bar{c}$

Fig. 1a

			b	b
	1	1	1	1
a	1	0	0	0
		c	c	

Fig. 1b

	$\bar{b}$	$\bar{b}$	b	b
$\bar{a}$	$\beta_0+M_0^3$	$\beta_1+M_1^3$	$\beta_3+M_3^3$	$\beta_2+M_2^3$
a	$\beta_4+M_4^3$	$\beta_5+M_5^3$	$\beta_7+M_7^3$	$\beta_6+M_6^3$
	$\bar{c}$	c	c	$\bar{c}$

Fig. 2a

			b	b
	1	1	0	1
a	0	0	0	0
		c	c	

Fig. 2b

Fig. 2/*a* illustrates in general the maxterm truth map for three variables while Fig. 2/*b* is the map of the problem in question. The simplified form in Fig. 2/*b* gives the values of the inverted coefficients $\overline{\beta_k}$ (and not the coefficients β_k as a maxterm M_k^n figures only when $\beta_k = 0$).

For example starting from the "1's" of the maxterm map, that is from the standard maxterm form

$$f^n = \prod_{k=0}^{2^n-1} (\beta_k + M_k^n) \tag{7c}$$

where β_k has the value "1" if M_k^n is not figuring in the switching function (in this case $\overline{\beta_k} = 0$) and β_k has the value "0" when M_k^n is present (in this case $\overline{\beta_k} = 1$).

By comparison of Eqs. (7a) and (7c) it becomes evident that $k = 2^n - 1 - i$ and $\alpha_i = \beta_k = \beta_{2^n-1-i}$ or $\overline{\beta_k} = \overline{\alpha_i} = \overline{\alpha_{2^n-1-k}}$.

In the example, examined formula (7c) yields:

$$f_1^3 = (\bar{a} + b + \bar{c})\,(\bar{a} + \bar{b} + c)\,(\bar{a} + \bar{b} + \bar{c}) \tag{7e}$$

which is the same expression as in the previously obtained Eq. (7e).

It is worth while mentioning that employing the maxterm map the symbolic form can be expressed as

$$f^n = \mathrm{A}(\mathrm{O}(\mathrm{W})) \tag{7d}$$

in contrast to Eq. (7b), here W denotes the set of the variables v obtained by direct read out from the "1's" of the maxterm map.

Summarizing the procedure for determining standard forms, Fig. 3 can be drawn, which is a generalization of the versions given in [9].

Finally, it must be noted that not only the standard forms but also the reduced forms can be obtained from the outlined procedure with the aid of the blocks of the maps.

In the minterm map in Fig. 1/b one second order and one first order block can be identified (see also Fig. 7/a). These give the reduction

$$f_1^3 = \bar{a} + \bar{b}\,\bar{c} \tag{1r}$$

which can be transformed via De Morgan's theorem as

$$f_1^3 = \overline{\bar{\bar{a}}\,\overline{(\bar{b}\,\bar{c})}} \tag{2r}$$

or

$$f_1^3 = \overline{a(b + c)} \tag{3r}$$

or

$$f_1^3 = \bar{a} + \overline{(b + c)} \tag{4r}$$

On the other hand, on the basis of the "0's" in the minterm map two first order blocks can be identified (see also Fig. 6/c) yielding

$$f_1^3 = \overline{ac + ab} \tag{5r}$$

and employing De Morgan's theorem

$$f_1^3 = \overline{(ac)}\,\overline{(ab)} \tag{6r}$$

or

$$f_1^3 = (\bar{a} + \bar{c})\,(\bar{a} + \bar{b}) \tag{7r}$$

This expression could also be obtained directly from the maxterm map. Finally

$$f_1^3 = \overline{\overline{(\bar{a} + \bar{c})} + \overline{(\bar{a} + \bar{b})}} \tag{8r}$$

Eqs. (1r). . . (8r) yield the eight reductions for the example in question.

2. The proposed method

Now the problem arises whether it is possible to immediately determine a certain desired standard form or a reduction selected beforehand. This question can be answered positively. The proposed method for immediate determination of standard forms or reductions was previously prepared and supported by the symbolic expressions summarized in Fig. 3. Each symbolic expression gives the structure of the standard form in question. In addition to this the method of read out from the truth maps is also fixed: The variable set V signifies the application of a minterm map, lower index 1 means a reading out based on the "1's" while index 0 means a starting point from the "0's", finally the plain set V of variables refers to the direct employment of the co-ordinates, on the other hand, NV means an inverse reading out of the co-ordinates.

Similarly W denotes the application of a maxterm map and, for example, W_1 means a direct reading out based on the "1's", while NW_0 refers to an inverse

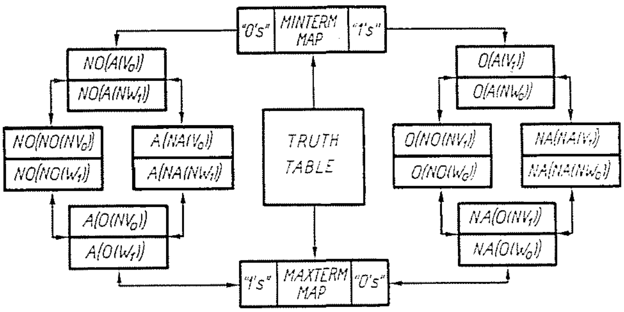

Fig. 3

reading out based on the "0's". Of course one sole map, for example, the minterm map will do.

For the sake of completeness Table 1 is constructed as a detailed illustration of the method suggested.

Table 1

Methods of reading out the co-ordinates of a special standard form

Application of a minterm map			Application of a maxterm map		
Standard form desired	Reading out from the "0's"	Reading out from the "1's"	Reading out from the "0's"	Reading out from the "1's"	Standard form desired
$O(A(V_1))$		directly	inversely		$O(A(NW_0))$
$NA(NA(V_1))$		directly	inversely		$NA(NA(NW_0))$
$NA(O(NV_1))$		inversely	directly		$NA(O(W_0))$
$O(NO(NV_1))$		inversely	directly		$O(NO(NW_0))$
$NO(A(V_0))$	directly			inversely	$NO(A(NW_1))$
$A(NA(V_0))$	directly			inversely	$A(NA(NW_1))$
$A(O(NV_0))$	inversely			directly	$A(O(W_1))$
$NO(NO(NV_0))$	inversely			directly	$NO(NO(W_1))$

By the way, in Table 1 some kind of duality can be observed. The dual pairs are: minterm map and maxterm map, "0's" and "1's", direct reading out and inverse reading out of the co-ordinates, consequently V_1 and NW_0, NV_0 and W_1 and so on.

3. Some illustrative examples

In the following part we can find some illustrative examples to show the effectiveness of the proposed method. We do not care about all standard forms, instead of this we concentrate our attention only to the standard forms NO (NO(...)), NA (NA(...)) that is, to the NOR and NAND logic, because

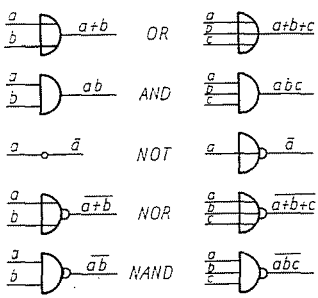

Fig. 4

Fig. 5a

Fig. 5b

in transistor switching circuits this standard form can most simply and naturally be realized.

In Fig. 4 the symbolic graphical notations applied in this paper are summarized for the OR, AND, NOT operations and also for the NOR and NAND operations and elements. These notations can be regarded as propositions, too. It is worth mentioning that the NOT circuit on the right-hand side is essentially nothing else but a NOR circuit for one variable, that is, for a NOR circuit the free inputs must be regarded as 0 signals, or they can also be the same signals as the first input (Fig. 5*a*). On the other hand, realization of a NOT circuit with NAND logic is demonstrated in Fig. 5/*b*. The free inputs must be 1 signals or the same signals as the first input.

Example 1. Let us determine the standard forms and reductions expressed by NOR logic for the case in Fig. 1/*b*.

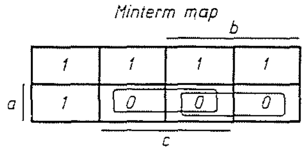

Fig. 6a

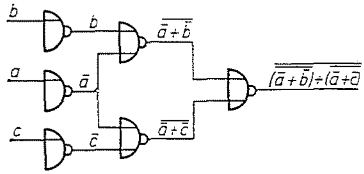

Fig. 6b

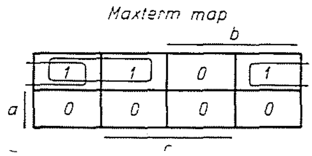

Fig. 6c

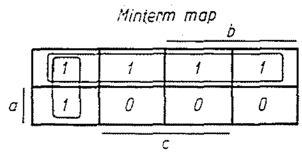

Fig. 7a

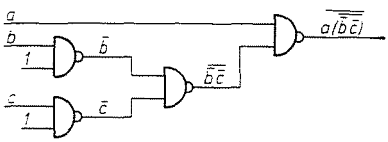

Fig. 7b

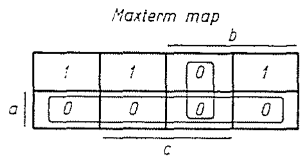

Fig. 7c

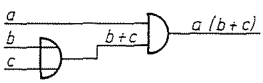

Fig. 8a

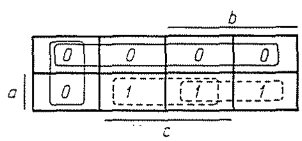

Fig. 8b

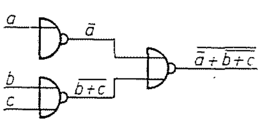

Fig. 8c

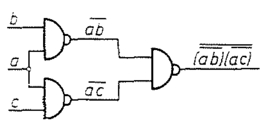

Fig. 8d

Applying the last row of Table 1, that is, the NO (NO (NV_0)) relation, we obtain from the second row of Fig. 1/*b* for the standard form

$$f_1^3 = \overline{\overline{(\bar{a} + b + \bar{c})} + \overline{(\bar{a} + \bar{b} + \bar{c})} + \overline{(\bar{a} + b + c)}}$$

and taking the two first order blocks in Fig. 1*b* (or in Fig. 6*a*) into consideration we obtain the reduction:

$$f_1^3 = \overline{\overline{(\bar a + \bar c)} + \overline{(\bar a + \bar b)}}$$

This expression, which is naturally the same as (8r), can be realized as illustrated in Fig. 6*b*.

The same result can be obtained of course, from Fig. 2*b* (or Fig. 6*c*) and by way of formula NO (NO(W_1)) in Table 1.

Example 2. Let us solve the previous problem by NAND logic.

From the second order and first order blocks in Fig. 1*b* (or Fig. 7*a*) and applying formula NA (NA(V_1)) we obtain:

$$f_1^3 = \overline{\bar{\bar a}\,\overline{(\bar b\, \bar c)}}$$

This expression can be realized as is shown in Fig. 7*b*. The same result can also be obtained starting from the maxterm map in Fig. 7*c* and by the use of formula NA (NA(NW_0)).

Example 3. The switching function $a\,(b + c)$ is given. This can be realized by OR-AND logic as shown in Fig 8*a*. Let us determine the NOR and NAND logic representations.

First of all the minterm map is constructed (Fig. 8*b*) taking into consideration that $a\,(b + c)$ has the form of A (O(NV_0)). Then applying relation NO (NO(NV_0)) our function can be written as

$$f_3^3 = \overline{\bar a + \overline{(b + c)}}$$

which can be realized as shown in Fig. 8*c*. Finally, employing expression NA (NA(V_1)) and the first order blocks in Fig. 8*b* we obtain:

$$f_3^3 = \overline{(\overline{ac})\,(\overline{ab})}$$

which can be represented as shown in Fig. 8*d*.

Example 4. The truth table of the imaginable eighteen basic logical or switching functions of the two variable a and b is summarized in Table 2.

Table 2

Basic logical or switching functions of two variable

a	b	f_0^2	f_1^2	f_2^2	f_3^2	f_4^2	f_5^2	f_6^2	f_7^2	f_8^2	f_9^2	f_{10}^2	f_{11}^2	f_{12}^2	f_{13}^2	f_{14}^2	f_{15}^2
1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
1	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
0	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

It must be noted that only ten of the functions have any meaning at all. These are summarized in Table 3.

Basic switching functions of two variables

Table 3.

Basic two-variable switching function	Minterm standard reduced form	Minterm truth map	Notation and denomination
f_1^2	$\bar{a}\,\bar{b}$	1 0 0 0	$a \downarrow b$, $a \overline{+} b$ NOR
f_2^2	$\bar{a}\,b$	0 1 0 0	INHIBITION
f_4^2	$a\,\bar{b}$	0 0 1 0	INHIBITION
f_6^2	$\bar{a}\,b+a\,\bar{b}$	0 1 1 0	$a \oplus b$ EXCLUSIVE OR
f_7^2	$\bar{a}+\bar{b}$	1 1 1 0	$a \mid b$, $a \overline{\cdot} b$ NAND
f_8^2	$a\,b$	0 0 0 1	$a \cdot b$ AND CONJUNCTION
f_9^2	$\bar{a}\bar{b}+ab$	1 0 0 1	$a \equiv b$ EQUIVALENCE
f_{11}^2	$\bar{a}+b$	1 1 0 1	IMPLICATION
f_{13}^2	$a+\bar{b}$	1 0 1 1	IMPLICATION
f_{14}^2	$a+b$	0 1 1 1	$a+b$ OR DISJUNCTION

Now let us express the then basic switching functions by NOR logic. Without going into details the results are summarized in Fig. 9. It is worth to mention that expression NO(NO(NV$_0$)) was applied. The fact can also be observed that f_i^2 and $f_{2^n-1-i}^2$ are inverse (complementary) functions, that is, each can be obtained from the other by negation.

In this respect the realization of function f_6^2 is very interesting being the complementary one of f_9^2. The latter contains five NOR elements. For negation one more element would be necessary, that is, altogether six elements would do. Instead of this f_6^2 can be realized through five elements.

Example 5. Let us solve the previous problem by NAND logic.

For this case the results are summarized in Fig. 10. According to Table 1 the expression NA (NA(V$_1$)) was chosen as a basis. Similar remarks as in *example 4* are also valid for this case.

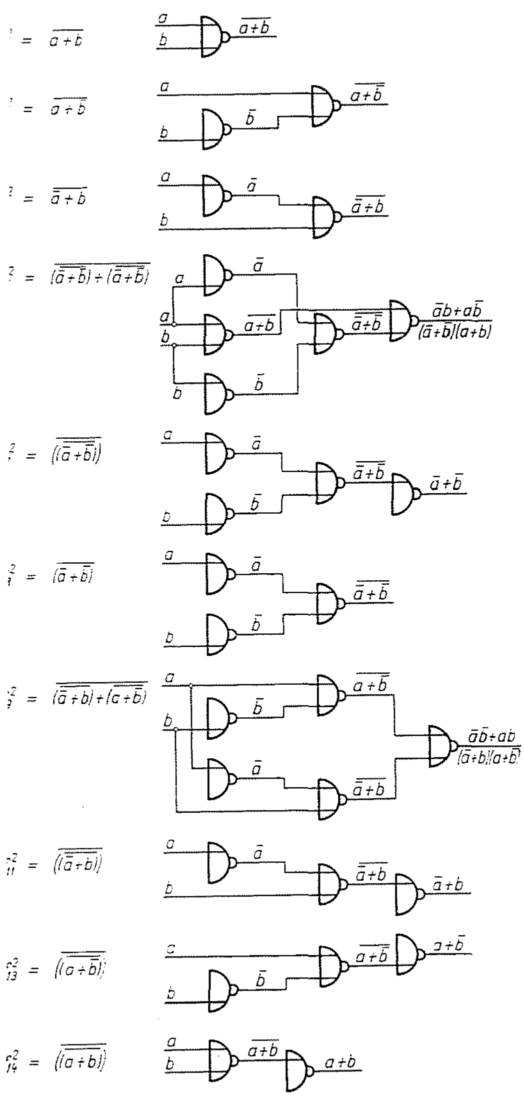

Fig. 9

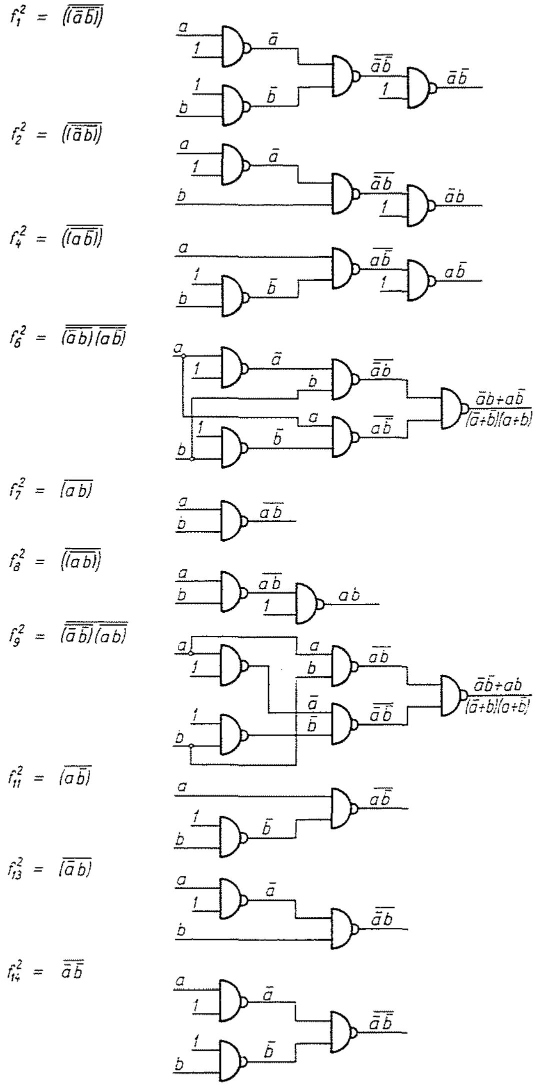

Fig. 10

4. Conclusions

In the foregoing treatise a general method was presented for the immediate determination of a special standard form or reduction. Only one of the truth maps, for example, the minterm map is necessary and each of the eight standard forms or reductions can directly be obtained at pleasure. The essence of the method suggested is summarized in Table 1.

The proposed method is perhaps a small contribution to the theory and practice of Boolean functions.

The significance of the method is particularly thrown into relief because in transistor circuits the NOR or NAND logic is of primary importance, opposite to the relay circuits, where the NOT-OR-AND logic serves as a basis. The suggested method gives a key to the systematic transformation from one logic to the other.

The method was demonstrated in several examples.

In the illustrative examples for the sake of simplicity, only two — and three — variable functions are considered. The method can be applied, of course, also to multivariable functions. But as all procedures also this method becomes more and more complex and laborious with the increase of the number of variables.

Summary

In this paper a method is presented which makes possible the immediate determination of a selected special standard form or reduction for Boolean functions using only one truth map, for example, the minterm map. The results are obtained via De Morgan's theorem, but with the method suggested, an application of De Morgan's theorem is not necessary at all. For the illustration of the proposed method a few problems are solved. In these examples emphasis is laid especially on NOR and NAND logic, having a particular significance in transistor logic circuits.

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