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AUTHOR Barker, Bruce O.
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ABSTRACT

This study introduces the concept of Fault Tree Analysis as a systems tool and examines the implications of Fault Tree Analysis (FTA) as a technique for isolating failure modes in educational systems. A definition of FTA and discussion of its history, as it relates to education, are provided. The step by step process for implementation and use of FTA is described, and current applications of FTA to education are analyzed. A Fault Tree prototype is presented to suggest solutions to a problem in private education. A glossary is given in the Appendix, as well as a schematic of a prototype FTA. (RAO)

FAULT TREE ANALYSIS: ITS IMPLICATIONS FOR USE IN EDUCATION

by

Bruce O. Barker

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Statement of the Problem

In recent years the amount of education related research has grown at an unprecedented rate. It can be said that in the educational world of the 1960's a knowledge explosion occurred and will undoubtedly continue through the 1970's and beyond. Prominent in this influx of knowledge has been the application of systems technology and systems analysis to aid in the solving of educational problems.

Analysis of a system, in relation to accomplishment of previously established objectives can be viewed in terms of two basic approaches: (1) analysis in terms of success or accomplishment of a system's purpose--that is, what must or should be done in order to achieve desired results; or (2) analysis in terms of failure or non-accomplishment of a system's purpose. Although failure prevention is becoming increasingly important, the general procedure of both the past and present seems to be to look at success factors. Yet, it seems much more difficult and time consuming to predict or determine what promotes success in a system than it does to isolate those factors which cause failure. Furthermore, among a panel of experts in any specified system, it generally is easier to achieve consensus as to what constitutes failure in a system than what constitutes success. Hence, in the field of education if decision makers can systematically isolate failure modes within a system, the probability for success will be enhanced. The problem is to explore and suggest a systematic approach to analysis of factors contributing to failure for the purpose of increasing success probability in education systems.

Purpose of Study

The purpose of this study is to introduce the concept of Fault Tree Analysis as a systems tool and to determine the implications of Fault Tree Analysis as a technique for isolating failure modes in educational systems. Specific objectives include:

1. To define Fault Tree Analysis and discuss its history as it relates to the systems approach.
2. To describe the step by step process for implementation and use of Fault Tree Analysis.
3. To identify what is presently being done in the United States with Fault Tree Analysis as it applies to education.
4. To present a Fault Tree prototype to suggest solutions to a problem in private education.

The purpose of this report, then, is to discuss and present to educators some background in Fault Tree Analysis as applied to educational planning, evaluation, and problem solving, together with an explanation of the present use of Fault Tree Analysis in education and an example of the technique as applied to a problem pertinent to private education.

REVIEW OF LITERATURE

Definition of Fault Tree Analysis

Fault Tree Analysis (FTA) is an operations research technique which has been used with success as the principle analytical tool of systems safety engineering on aerospace projects. As used in the aerospace industry, Powers (1974) states that Fault Tree Analysis refers to event squences which lead up to a significant predefined failure such as loss of mission where there exists potential for injury of personnel and/or large economic losses. Crosseti (1971, p. 53) adds:

> Fault tree analysis provides a functional development of a specific final undesired event through the logic statements of the conditions which could cause the event. Once the final event is defined for assessing system performance, this method provides a concise and orderly description of the various combinations of possible occurrences within the system, that could result in the predefined event.

As used in aerospace and other scientific disciplines which involve hardware systems, Powers (1974) further defines Fault Tree Analysis by indicating that it is a graphic representation of the logic which describes information flow (in this case failure propogation) in the processing network. He says that the basic building blocks of the fault tree are composed of the logical interconnections among event sequences, known as logic gates. A logic gate defines the input conditions which must be present in order for a failure sequence to move or propogate up the tree. There are two basic logic gates: the "and" gate, and the "or" gate. Both will be discussed in depth later in this paper.

Recht (1965) defines FTA as a method of analysis in which an undesired event is selected and all the possible happenings that can contribute to the event are diagrammed in the form of a tree. The branches of the tree are continued outward and downward from the undesired event until independent events are reached. Probabilities can be determined for the independent events, and both the probability of the undesired event and the most likely chain of events leading up to it can be computed.

Fault Tree Analysis differs little in definition among disciplines or between "hardware" and "human" systems. As it related to human systems--specifically to education--Stephens (1973, 1974, 1976) has given the most concise definition. He says that FTA is a technique for increasing the probability of success in any system by analyzing the most likely modes of failure which could occur within the system and then suggesting high priority avoidance strategies for those failure modes. A fault tree (sometimes referred to as an "event logic network") provides a concise and logical step-by-step description of the various combinations of potential or possible occurrences within a system which could result in the failure of the system. It is a graphic protrayal or diagram which systematically depicts the probable failure event sequences and the interactions among these sequences which can lead to failure of a top, undesired event. The objective is to identify and isolate possible failure modes and thereby avoid them.

In 1973 (p. 3) Stephens wrote:

> The process of fault tree construction starts with a statement of a critical undesired event which one wants to prevent from happening. The fault tree is then constructed

according to a series of logic steps, showing precisely how a given failure [failure as here used means the inability of a system or a portion of a system to perform its expected function(s)] event could occur. When the tree is finished, mathematical formulas are [can] be applied to determine the strategic paths leading to the top (most general) undesired event. On large trees the data can be fed into a computer for simulation and quantification.

The value of finding the critical or strategic failure path through FTA is that it provides a clear indication to the decision maker(s) as to the weakest link in the system and thereby provides information for setting priorities in the decision making process (Witkin, 1971).

The name "Fault Tree Analysis" is derived in the fact that the graphic portrayal of a functional system which has undergone the process of Fault Tree Analysis utilizes a branching process similar in outline to a coniferous tree (Stephens, 1971).

To conclude, the fault tree method of analysis takes the approach of looking at and analyzing the most undesirable events which could occur within a system and then searching for and analyzing failures in sequence which could lead to these undesirable events.

History of Fault Tree Analysis

The development of FTA is an outgrowth of the systems safety approach (Recth, 1965) initiated in the space industry in the late 1950's and early 1960's. Fault Tree Analysis provided an added dimension to the systems safety approach by introducing the concept of failure prevention. A full appreciation and understanding of the history of FTA requires the necessity to view FTA in the context of systems safety analysis. Recht (1965, p. 38) recounts the origins of system safety analysis:

> The history of systems safety analysis really began in the aerospace industry. It was the result of the extremely high reliability and safety specifications demanded by the space and military requirements and the fact that the time honored production sequence was no longer practical.
>
> For example, until recently when a new aircraft was developed, it was first designed, then an experimental model was built, and finally it was test flown to determine its capabilities and flaws; the information obtained indicated the necessary design changes and the cycle was repeated until the performance specifications were met. Today's aircraft and missles are so complex and costly and the specifications are set so high that this procedure had to be changed. Moreover, missile flight tests involve loss of the model with only limited telemetry data obtained. Today the "bugs" must be found and corrected as far as possible in the design stage using analytical technique.
>
> The result is the development of the systems approach to safety. The aircraft or missile is examined from this point of view and the effects of any failure or malfunctions on the operation of the aircraft are evaluated to determine the principle design defects which need to be fixed. For these complex systems sophisticated analytical methods have been developed... . Thus the test pilot has been replaced by a systems safety engineer... .

Fault Tree Analysis has its beginnings in the above described setting. Fussell, et al. (1974, p. 51) relates:

> In 1961 the concept of fault tree analysis was originated by H. A. Watson of Bell Telephone Laboratories to evaluate the safety of the Minuteman Launch Control System. The technique was further developed and refined by a Bell Telephone Laboratories study team.

Engineers at Bell Laboratories discovered that the method used to explain the flow of "correct" logic in data processing equipment could similarily be used for analyzing the "false" logic resulting from component failures (Witkin and Stephens, 1968). A team of analysts at the Boeing Company later modified the technique so that the quantification (prioritizing and determining the probability of occurrence of failure events) of the fault tree could be accomplished via a digital computer (Fussell, et al., 1974).

Although the concept of FTA is of recent origin (1961), the idea of looking for breakdowns in a system is not entirely new. Other techniques such as the Critical Incident Technique, Cause and Effect Analysis, etc. bear a superficial resemblance to Fault Tree Analysis. For a description of these techniques see Stephens, 1972.

History of Fault Tree Analysis as related to education

Until 1967, few attempts had been made to apply the concept of FTA entirely to human systems, chiefly because analysts trained in the technique were mainly engineers concerned with systems safety without a "feel" for behavorial systems, and partly because no adequate method of defining strategic paths (the most critical sequence of failure events) had been demonstrated in behavorial systems (Stephens, 1973).

The first full scale application of FTA to educational planning and evaluation was that done by Witkin and Stephens (1971) in 1967-68 under the auspices of the Alameda County PACE (acronym for Projects to Advance Creativity in Education) Center, Hayward, California. This initial application of FTA to education was in the interest of discovering a predictive tool which would act as a sort of "early warning" signal to educators concerning critical needs to which they should direct their attention.

Regarding this first use of FTA as it applies to education, Witkin writes (Witkin and Stephens, 1968, p. 7):

> In the fall of 1966, the research specialist of the [Alameda County PACE] Center was put in touch with Kent Stephens, then a member of an aerospace group in the Boeing Company, and first learned about fault tree analysis. Subsequently, Stephens and two colleagues, David Haasl and Jon Stephens, visited the PACE Center to explain the principles of fault tree analysis, and in May 1967 they conducted a week-long training program for school administrators and other interested persons under the sponsorship of the [PACE] Center and the Alameda County School Department. There, the first trees applied to educational problems were drawn and the possibilities of the technique were explored.

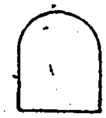
Dr. Kent G. Stephens was a member of the Boeing team which modified the fault tree technique in relation to the quantification of failure events, enabling it to be accomplished with a digital computer (Witkins and Stephens, 1968), and Wood (1975, p. 2) has identified Stephens as "...the father of the quantification and application of Fault Tree Analysis to education." Dr. Stephens is currently an Associate Professor in Education at Brigham Young University, Provo, Utah.

Fault Tree Symbols and Definitions

In this section the basic symbols of Fault Tree Analysis are presented and defined and the concept of logic gates is clarified.

Logic gates

The fault tree is constructed by showing the relationship between various kinds of events which could cause failure of the system. These relationships are symbolized by logic gates. The concept of logic gates is the heart of the fault tree technology and they are the factor which causes it to differ from other forms of analysis. Stephens (1973, 1974, 1976) has described the concept of logic gates extensively and indicates that two principle kinds of logic gates exist, the AND gate and the OR gate. All other gates used in FTA are derivatives of these two types.

Graphically, the AND gate is depicted by the symbol  and is used when two or more events must <u>coexist</u> in order to produce the more general event. Figure 1 depicts the portrayal of events related by an AND gate as they would appear in a fault tree.

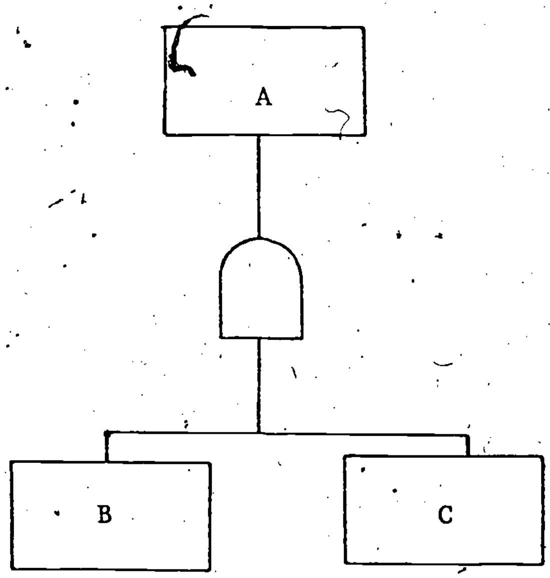
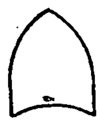


Figure 1. The AND gate.

This tree would be read; Events B and C must coexist in order to produce Event A; or, the output A can occur <u>only</u> if the inputs B and C coexist. The mathematical equivalent of this is $A = (B \wedge C)$.

The use of the AND gate(s) occurs much less frequently (in some cases not at all) in behavorial systems than in hardware systems.

The OR logic gate occurs most commonly in behavorial systems. It is used when, of two or more possible inputs to an event, <u>any one</u> alone could produce the output. The OR gate is depicted graphically by the symbol . Figure 2 depicts the portrayal of events related by an OR gate as they would appear in a fault tree.

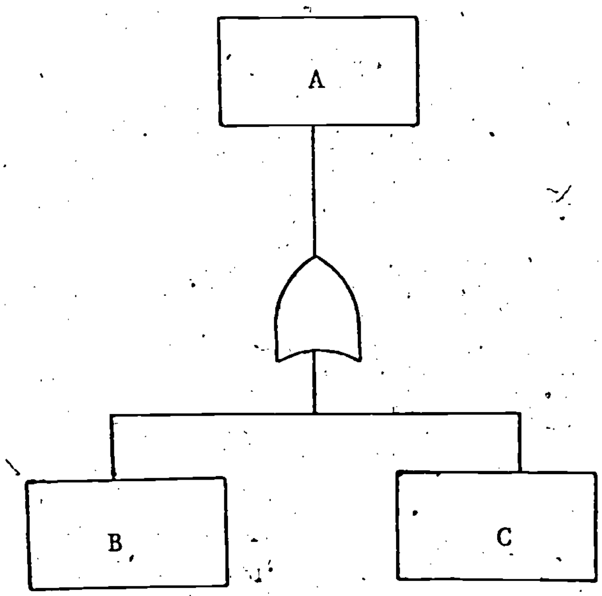


Figure 2. The OR gate.

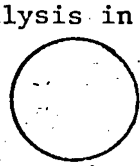
The tree depicted in Figure 2 would be read: Either B <u>or</u> C events alone will produce Event A. The mathematical equivalent of this is A = (B C).

Stephens (1976) notes two general kinds of OR gates--the INCLUSIVE OR depicts the situation in which either Event B or C or both could result in Event A. The EXCLUSIVE OR situation differs in that either Event B or C could produce Event A, but both B and C could not occur at the same time. It should be noted that with either the AND gate or the OR gate logic, more than two inputs may exist to any event, however, it is always necessary to have at least two inputs.

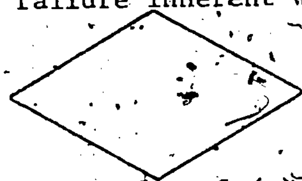
<u>Basic fault tree symbols</u>

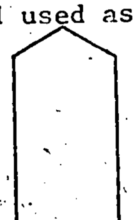
Besides logic gates, the other set of symbols used in FTA depict the types of inputs and outputs or events. Events, whether they be inputs or outputs, are classed according to their nature. Stephens (1973, 1974, 1976) suggests the following symbols as those most commonly used for fault trees:

1. Rectangle:  Identifies an event that results from a combination of less general fault events through an associated logic gate. All events symbolized by rectangles have additional development or analysis in the fault tree.

2. Circle:  Identifies a basic failure event in which no further development is required. The decision regarding whether the

event is a basic one or not depends largely on the perspective of the analysis. A basic failure event occurs when the definition of an event is sufficiently explicit to satisfy the purpose of the analysis. It is a failure inherent within the unit of analysis.

3. Rhombus:  Identifies an event which is not developed further because of (a) insufficient information, (b) very remote likelihood of occurrence, or (c) due to other constraints (eg. time, money, etc.) which preclude further analysis. If at a later date, however, constraints are removed and it is desired to analyze the rhombus in greater depth, then it can be changed to a rectangle in which case it could be developed and analyzed further (Stephens, 1973). The rhombus has no relationship with the diamond used as a decision point in flow charting.

4. House:  Identifies an event which, under normal conditions, is expected to occur in the system defined and by itself may not cause a failure event. The importance of noting it, however, is that when combined with other events it might contribute to a failure event.

These provide the basic symbols used in fault tree analysis and construction. A few other symbols and definitions have been identified by Stephens (1973) and appear in the appendix of this paper.

The symbols reviewed, displayed in Figure 3, a rudimentary fault tree branch which is read as follows: "Event A can be produced either by Event B or Event C or both. Event B can be produced only by the coexistence of Events D and E. Event C can be produced either by Event F or Event G or both." (Stephens, 1973, p. 10; 1974, p. 6; 1976, pp. 7-8) Event E is viewed as a primary or a basic failure event and Event F is an event which is normally expected to occur within the system, but which can contribute to Event C. Events D, E, F, and G--at the bottom of the tree--require no further analysis or development.

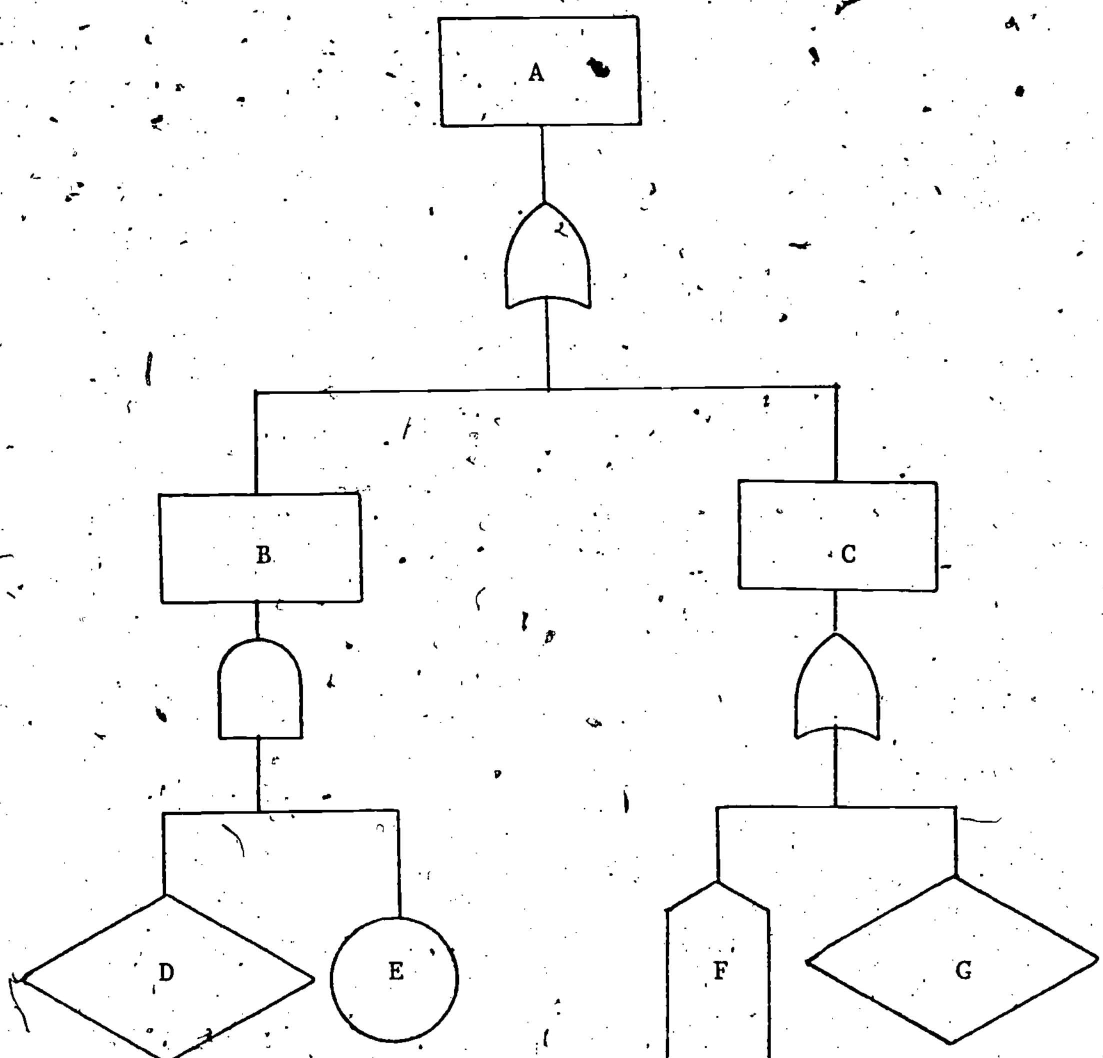


Figure 3. Illustration of a fault tree branch

The bottom of the tree for any fault tree branch should always have events depicted by the circle, rhombus, or house. These signify the end of development. In the example portrayed in Figure 3, there are two branches of the tree and three levels of development or analysis.

Steps in Fault Tree Construction

It must be remembered that the fault tree method was initially developed for use in hardware systems. Although relatively little has been published on the concept, a few scattered articles explaining the procedures for conducting a Fault Tree Analysis have appeared among several disciplines (see Powers, 1974; Eisner, 1972; Vesely, 1970; Evans, 1974; Fussell, et al., 1974; Crossitti, 1971). Although similar, procedures vary somewhat among authors and between disciplines. Since the purpose of this paper is to explore Fault Tree Analysis in an educational context, references to technique and methodology will be taken chiefly from Stephens who has pioneered the concept in education (Wood, 1975) and behavorial systems. In 1968 Witkin and Stephens wrote that the p nciples of Fault Tree Analysis, as they applied to education, were undergoing further development and were subject to change." Hence, in considering the general steps in fault tree construction and analysis, care will be taken to cite the most current references available.

The present state of the art identifies the following as general steps in Fault Tree Analysis (Stephens, Class Lecture, October 28, 1975):

1. Systems definition
2. Mission analysis
3. Identification of undesired events
4. Fault hazard analysis
5. Qualitative fault tree construction
6. Quantitative evaluation
7. Formulating recommendations

Systems definition

Systems definition essentially entails formulating the exact problem to be analyzed. Systems definition should specifically state the goals and/or objectives of the system to be analyzed. When properly stated these goals and/or objectives become known as the mission statement. The mission statement should include an explanation of the system restraints and a recognition of the system bounds. Bounds are those factors over which there is no control and restraints identify factors over which there exists some control (Stephens, Class Lecture, October 28, 1975).

Mission analysis

Mission analysis includes the mission statement--that is, what is to be accomplished, and it identifies the specific performance requirements of criteria necessary in order to successfully complete the mission within the bounds and constraints set in the systems definition. It is a statement of the mission along with the required functions and tasks necessary to complete the mission (Witkin, 1971).

The mission analysis is derived by systematically considering the major functions necessary to accomplish the mission and those important tasks which must be accomplished within each function. Stephens (1972) states that two steps are present in performing a mission analysis: (1) The first step is to list the major functions that will be needed to accomplish the mission statement given previously in the systems definition. This is referred to as function analysis, and provides an answer to the question, "What are the major functions needed to accomplish the mission or goal statement?" (2) The second step in performing a mission analysis is to consider the major tasks which must be accomplished within each function and is referred to as task analysis. The process, as here described, is illustrated in Figure 4 (Stephens, 1972, p. 25).

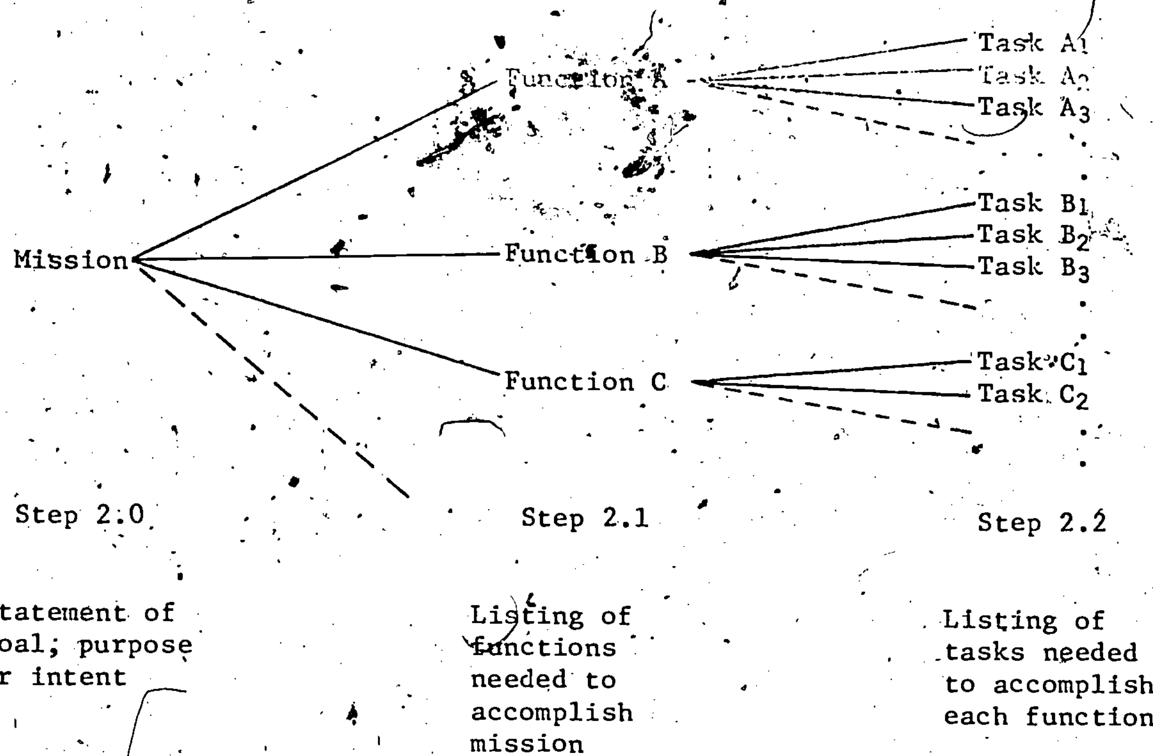


Figure 4. Schematic showing major steps in mission analysis.

The performance of a mission analysis permits the performance of function and task analysis. They, in turn, greatly facilitate Fault Tree Analysis during qualitative fault tree construction because they allow the identification of specific failure events more readily and effectively than with simply an examination of missions and major functions (Stephens, 1972). In short, mission analysis enables the analyst(s) to see the system under study in a broad perspective and to identify specific problem areas for later analysis.

Identification of undesired events

Based on the mission or goals statement of the systems definition and the mission analysis, the analyst or team of experts conducting a FTA would list those events which they do not want to happen relative to the system under investigation. These events should be written in terms of failure and are the means of identifying the major undesired events which could occur in the system.

It may appear that selection of the major undesired events based on the mission analysis, and in fact the entire analysis for failure in the fault tree process is simply the logical reciprocal of analysis for success. To a degree this is true, however, experience has shown (Stephens, 1976) that failure analysis gives added perspectives on a system which is far beyond the notion that analysis for failure is merely the logical inversion of analysis for success.

By examining failure modes, the fault tree process generates questions about a system which would not occur under the usual conditions of success analysis. Furthermore, analysis for failure is generally much more conducive to consensus formation among a group of experts than is analysis for success. It appears easier to come to agreement on what not to do, than to consider and attempt to agree on the many facets of what should be done.

Fault Hazard Analysis

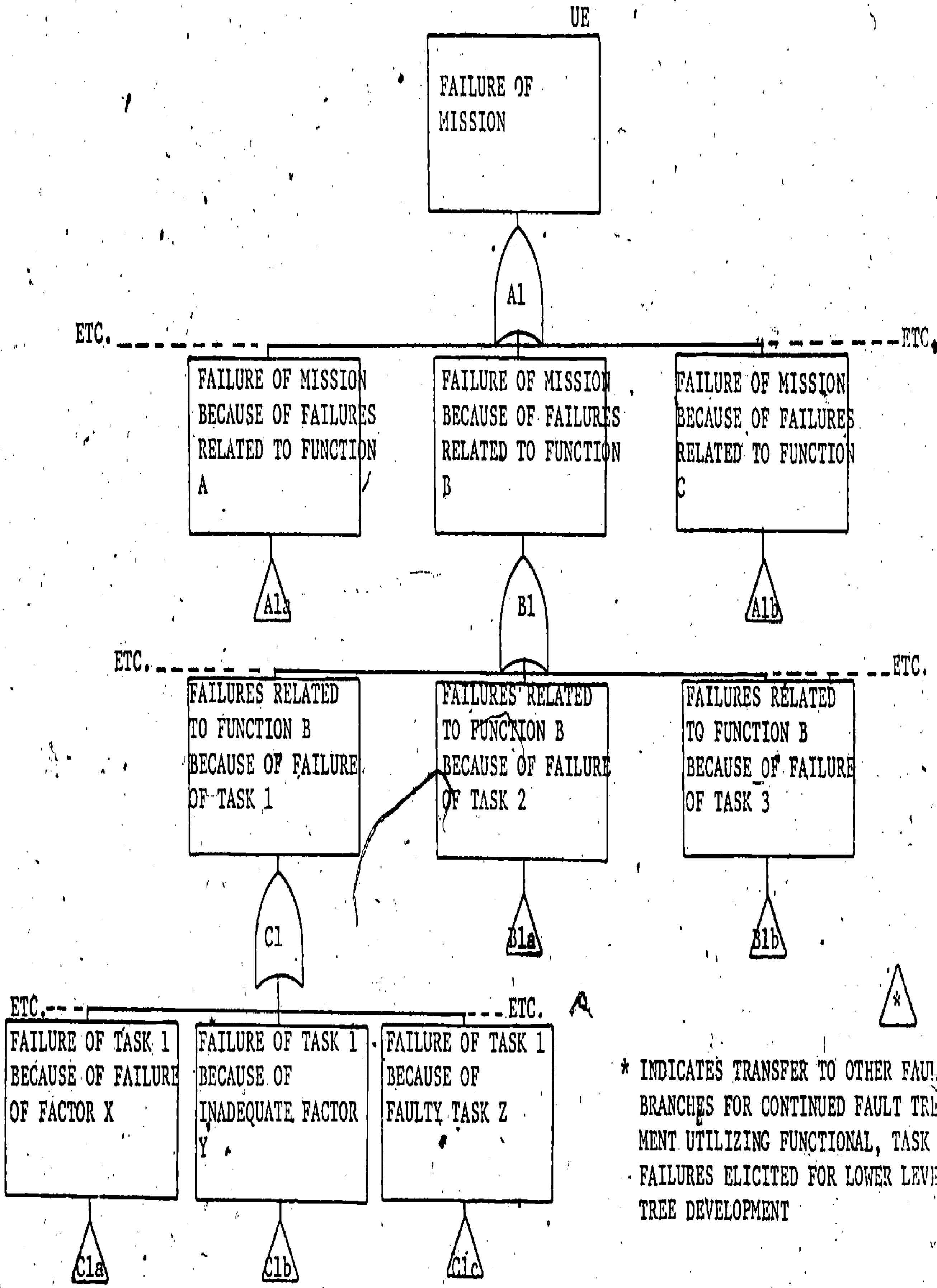
Once the major undesired events have been identified they are ranked in relation to each other, in order to determine the highest priority undesired event. There is no hard set rule as to how the ranking can or should be accomplished. This determination and selection of the highest priority undesired event is termed Fault Hazard Analysis (Stephens, Class Lecture, October 28, 1975).

Qualitative fault tree construction

Qualitative fault tree construction begins after the selection of a top or most general undesired event. Fault tree construction is generally the most tedious and the most critical aspect of Fault Tree Analysis, for at this point the analyst begins sketching or drawing the fault tree. It should be remembered that the fault tree consists of events, interrelated by logic gates, resulting in sequential pathways of potential failure. Analysis begins with the precise statement of a predefined undesired event (UE) of critical importance. An example may be failure of the entire system expressed in terms of failure of the mission, or it may be a failure identified with some function or task crucial to the success of the mission. Regardless, it stands at the top of the tree, and analysis proceeds downward and outward. Inputs to the UE in turn become contributing failure events in a perceived cause and effect relationship (Stephens, 1976). The purpose now is to determine the possible modes of occurrence of the UE.

In drawing the fault tree, the analyst should have a good working knowledge of the system under analysis, or immediate access to experts who do.

Scoping the tree. After selection of the UE, the initial phase and general format of qualitative fault tree construction is to look closely at the mission analysis as depicted in Figure 4 and convert it into a graphic fault tree. Figure 5 portrays the mission analysis converted into the form of a fault tree. This process is called "scoping the tree" (Stephens, Class Lecture, November 11, 1975) and is the basis of additional development and accurate analysis. The scoping of the tree generally results in three distinct levels of development (mission, function, task). Stephens (Class Lecture, November 11, 1975) has stated, "The first three levels of the tree are usually the policy levels."



* INDICATES TRANSFER TO OTHER FAULT TREE BRANCHES FOR CONTINUED FAULT TREE DEVELOPMENT UTILIZING FUNCTIONAL, TASK OR OTHER FAILURES ELICITED FOR LOWER LEVEL FAULT TREE DEVELOPMENT

Figure 5. General format for qualitative fault tree construction, "Scoping the Tree."

<u>Methodology and depth of resolution.</u> In generating the fault tree, the basic question seems to be: "Given a specified UE, what sequences of events may possibly take place to result in the actual occurrence of the UE?" Drawing the fault tree is a deductive process and the general methodology is to identify predecessor events from the top of the tree successively down to initiating or primal failure events. Once constructed--and in the process of construction--the tree is read from the top down, noting at each level whether events are inputs to AND gates or OR gates.

In the process of qualitative construction, the analyst should be extremely specific in formulating failure statements. Every failure statement should contain four vital words: "Failure of...because of..." (Stephens, Class Lecture, November 18, 1975) or a suitable euphemism for them.

In making failure statements a suffix-prefix relationship should exist--that is, the suffix of an output failure event becomes the prefix of an input failure event. In addition, failure statements should attempt to use a descriptive adjective, usually with a negative connotation. For an example of the suffix-prefix relationship and descriptive adjective see Figure 6:

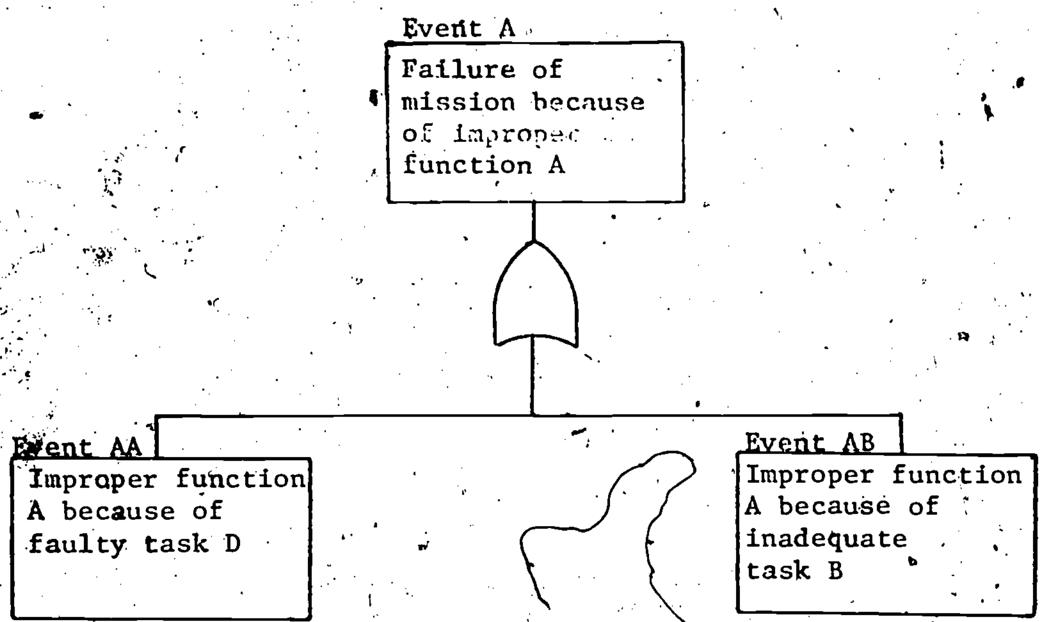


Figure 6. Suffix-prefix relationship, descriptive adjective.

In this example (Figure 6), the word improper in Event A is a negative descriptive adjective and also the suffix to the failure statement of Event A. In Event AA, the word improper maintains its role as a negative descriptive adjective but now is the prefix to the failure statement of Event AA. The same is true of the word improper in Event AB. In this example it is understood that Event AA and Event AB both require further development.

There are no firmly set rules in breaking events down from one level to another. The general procedure is to ask questions regarding each event, chiefly, "What are the immediate probable causes of this event?" (Stephens (Class Lecture, November 11, 1975) has suggested a "Systematic Five Step Approach to Qualitative Fault Tree Development" for consideration in the development of each failure event:

1. Seek expert advice from authorities--of which you may be one--in looking for contributing factors which can cause failure of each event.
2. Consult printed literature. This may involve specialized research to become better acquainted with the system being analyzed.
3. Brainstorm with a group. This triggers thinking from others and often is a means of having one thought build in another.
4. Consider all possible primary, secondary, and command failures. A primary failure, represented by a circle, is a basic failure which is inherent in the unit of analysis and needs no further development. A secondary failure is represented by either a rectangle or a rhombus, depending on whether the analysis is to be developed further. It is an environmentally induced failure. A command failure is one in which the component is ordered into a "failed state." It does not represent failure of the component itself. Command failures can be represented by either a rhombus or a rectangle.
5. Attempt to locate the input, processing, and output failures of each event. This is accomplished by systematically asking questions regarding each event to determine those factors which could potentially contribute to failure of the event. For example, failure of a certain portion of the system may be attributable to failures of input from another part of the

system, failures of processing within a specific portion of the system, or failures of output to another part of the system.

It should be remembered that in effect Fault Tree Analysis the purpose of FTA is not to analyze all the possible failure events, just the major ones. The above suggestions are helpful mainly as checks for the analyst to be sure that no important events are omitted.

As the analysis proceeds, it will be found that very similar events, or even identical ones will often show up in different branches of the tree. This is a signal to the analyst to examine them in more detail, particularly if it is felt that the likelihood of their occurrence is high.

The analysis will be more accurate and efficient if it is done horizontally rather than vertically (Stephens, 1973)--that is, if all the inputs to an undesired event are generated at the same level before proceeding to the next level. The analysis need not proceed any further than the analyst desires. Some events may be represented by 12 levels, whereas others may be developed to only two. The general rule is that each failure event should be developed to a point where cause and effect relationships can take place (Stephens, Class Lecture, November 11, 1975). The bottom of the tree for any branch will always have terminal events depicted by a circle, rhomubs, or house. For each event represented by a rectangle, there must always be at least two or more input events.

Validity of the tree. Once the tree has been completely drawn it is validated wherever each terminal event occurs. The purpose is to determine that the tree is thorough, properly drawn, and is true or correct to the system being analyzed. The process for validation is as follows (Stephens, Class Lecture, November 11, 1975):

1. Each rectangle should state an undesired event.
2. Each terminal event should be studied closely and the question asked, "If this event really happens, is there any way in which it could be avoided?" If any way can be found to avoid occurrence of the event or an exception found to it, then an AND gate should be drawn above the event (it would replace the OR gate if there was not an AND gate previously) and a new event explaining the exception would be inserted in the tree. Simply stated, the tree is validated at all bottom or terminal events by considering whether it is possible to add AND gates and determining where they should be placed.

Labeling events in the completed fault tree. Prior to quantitative evaluation, failure events in the completed fault tree are labeled for quick and accurate location within the tree. The method for labeling events, designed by Stephens (Mimeographed Paper, 1975), uses a combination of the letters A-Z to identify each event. This combination constitutes what is called the "location code" and works as follows: (a) The code for a level one event is A, B, C,...Z. (b) The code for a level two event under Event B would be, BA, BB, BC,...,BZ. (c) The code for a level three event under Event BB would be BBA, BBB, BBC,...,BBZ. (d) etc. (see Figure 7). The number

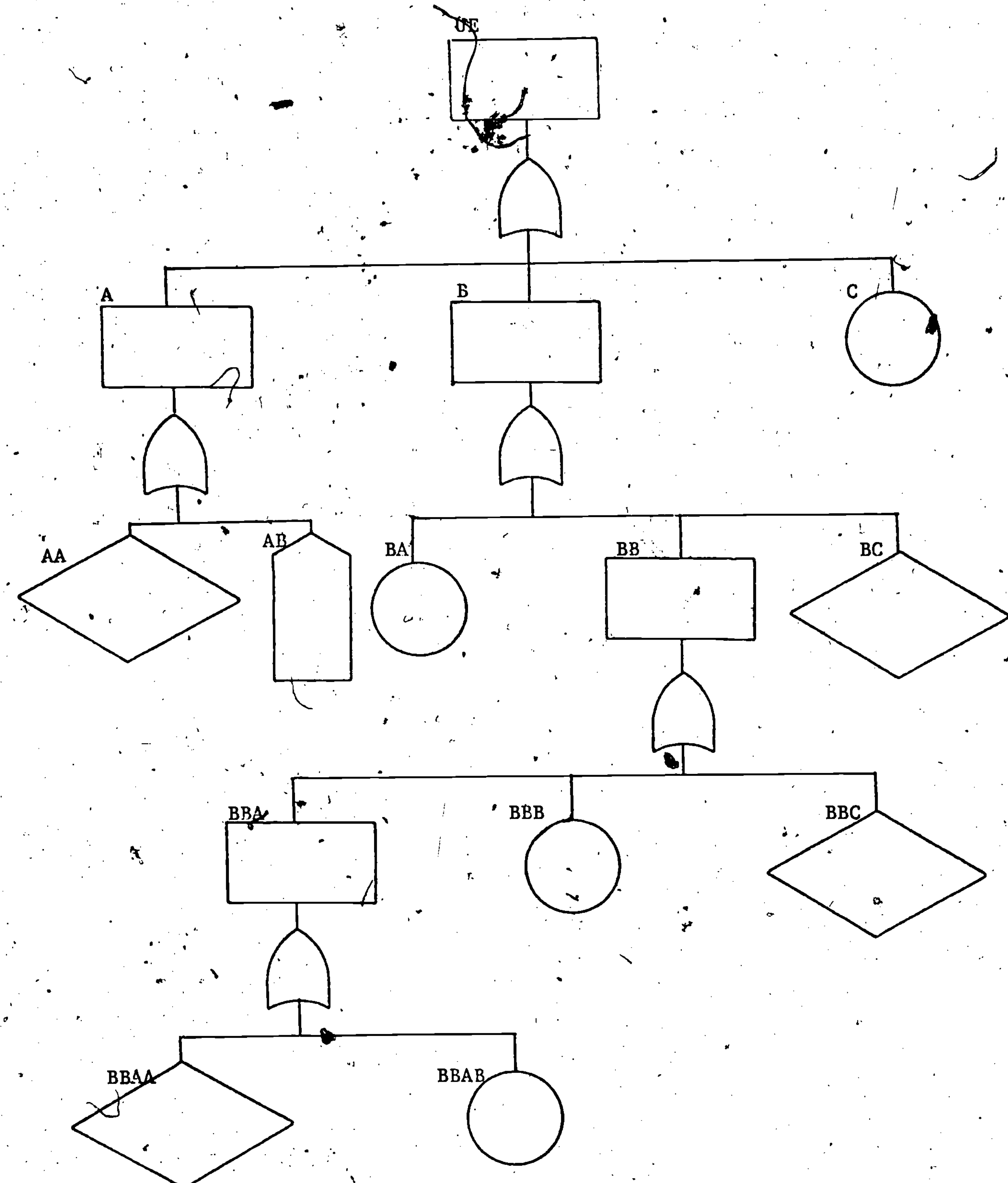


Figure 7. "Location Code" for labeling events in the completed fault tree.

of letters in a location code indicate the level number of that event. For example, Event BBC is a level three event.

Quantitative evaluation

It is not necessary for most of the team members engaged in qualitative fault tree development or quantitative evaluation to know more than the rudiments of fault tree principles (Stephens, 1976). Nor is it the intent expressed in this paper to go into a detailed account of the mathematical principles upon which quantification of FTA, as developed by Stephens, is based. Nevertheless, an explanation of the meaning of quantitative evaluation of Fault Tree Analysis is necessary and some basic principles related to it should be understood.

Quantitative evaluation (quantification) is the prioritizing and ranking of specified failure events against each other in order to determine high priority failure event sequences--the likelihood of occurrence of fault events. The objective is to identify and isolate a strategic path (critical path) of failure events leading from the bottom of the tree directly to the top. A primary strategic path (one of greatest emphasis), as well as a secondary strategic path, alternate strategic path, etc. can be identified. The importance of finding the strategic path is that it is a clear indication to the decision maker(s) as to the weakest links in the system and provides information necessary for correct decisions (Witkin, 1971).

The methodology used in the aerospace industry to arrive at quantification is not applicable to educational and social systems due to its objectivity. Accordingly, Stephens (1972) derived a subjective quantification technique for strategic path analysis to be used specifically on fault trees drawn for social systems. This technique is based on (1) an approach utilizing expert judgments based on training, experience, and in some cases research data; and (2) through formulas derived from Markov Processes and Boolean Algebra to yield strategic event values in order to identify strategic paths of interest by introspection. An explanation of the mathematical principles is beyond the scope of this paper.

The method for collecting and organizing expert opinion is achieved via a Modified Delphi Approach devised by Stephens (1976, p. 13). The process utilizes four basic subjective judgments as follows:

1. Starting with the top UE, rank in order of relative contribution (or importance) each of the failure events leading into it.

   For all of the inputs through a given logic gate to a single more general event, determine the percentage contribution made by each event to the more general failure event above it. Percentages should sum up to 100 for each event.

2. Determine confidence in the percentages (strong, moderate, and weak are commonly used).

   Repeat the above two steps for the inputs to each failure event, working systematically down through the tree.

3. Determine the appropriate frequency rating for each terminal event at the bottom or lowest level only for each branch of the tree (rarely, periodically, and frequently occurring are commonly used). The rating for each input to an event is determined independently of the other inputs for that same event.

4. Determine the rectification for each end (terminal) or bottom event only (permanent damage or impossible to rectify, difficult to rectify, and easy to rectify are commonly used).

An FTA computer program is on file at Brigham Young University designed by Stephens (Collings, 1975), which can be used to determine algebraically the relative probability of occurrence of failure events for deriving strategic paths (as well as for drawing the tree). For trees of less than 300 events, the mathematical calculations can be done by hand, however, this can be somewhat time consuming. For trees with over 300 events, and where it is the desire of the analyst to determine the strategic path via a computer program, Stephens (Class Lecture, December 2, 1975) has diagrammed a FTAP (Fault Tree Analysis Program) Quantification Input Form to aid in the process. The input form (see Figure 8), an extension of the Modified Delphi Approach used by Stephens is extremely helpful in recording the four basic subjective judgments discussed earlier. Using the form, failure events can be entered into the computer to yield strategic event values in order to identify strategic paths of interest. The FTAP Quantification Input Form and FTA computer file at Brigham Young University is capable of handling a fault tree of any configuration subject to the following limitations:

1. up to 16 levels of events
2. up to 26 events below a rectangle event
3. up to 2048 events in the fault tree

On small trees (less than 300 events) much valuable information can be gained about the system by simply inspecting the tree without necessarily completing the quantification. Events could be subjectively ranked against each other on each level to determine the strategic path without calculating the relative probability of occurrence.

PAGE ___ OF ___ RATER'S INITIALS

EVENT NAME: 16	EVENT[1] TYPE 18	GATE[2] 19	RANK 21	RELATIVE CONTRIBUTION 24 25		CONFIDENCE 28 (STRONG, MODERATE, WEAK)	FREQUENCY[3] 30 (FREQUENT, PERIODIC, RARE)	RECTIFICATION[3] 32 (PERMANENT, DIFFICULT, EASY)
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
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					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E
					%	S M W	F P R	P D E

1. TYPES OF EVENTS ARE: R - RECTANGLE D-DIAMOND

2. FOR RECTANGLE EVENTS ONLY. A - AND O - OR I-INHIBIT

3. FREQUENCY AND RECTIFICATION ARE NOT MARKED FOR RECTANGLE EVENTS.

Figure 8. FTAP Quantification Input Form.

Formulating recommendations

The final step in conducting a Fault Tree Analysis is to make recommendations based on the qualitative construction and the strategic path analysis derived during quantification. In addition, through the drawing of a fault tree and its analysis, an individual or team of experts can easily identify areas in which special care should be given within a system to better insure success. If the analysis is made during the design of a new program, the decisions based on it could confirm original feelings or lead to design changes. Recommendations based on the completed tree and identification of the strategic path may lead to reallocation of resources, installment of backup systems, monitoring of paths with high failure potential, provisions for improved communications, or the taking of corrective action which seems advisable (Stephens, 1974, 1976). Furthermore, visually displaying the completed fault tree and discussing the strategic paths with personnel at various levels of the organization often results in the formation of excellent suggestions for improvement and creates an appreciation for the entire system seen as a whole.

One of the great values of FTA, as it relates to the formulation of recommendations, is that emphasis is focused largely on the bottom levels or terminal events of the tree. If each bottom event is avoided or rectified, then logically the entire sequence of failure events above it would likewise not occur (Stephens, Class Lecture, December 2, 1975). Hence, in formulating recommendations, not only is the strategic path investigated closely, but also each terminal event of interest.

This concludes a description of the general steps in fault tree construction and analysis. It is important to note that the fault tree approach can be used in a more simplified and abbreviated form and still be very useful. In fact, it has been demonstrated by decision makers that they could derive useful information from any of the steps followed in performing a Fault Tree Analysis (Stephens, 1974).

Present Use of Fault Tree Analysis in Education

As indicated earlier in this paper, the first full scale application of FTA to education was pioneered in 1967-68 by Witkin and Stephens under the auspices of the Alameda County PACE Center, Hayward, California (Witkin and Stephens, 1968). The purpose of that study was to develop a master plan of occupational preparation for youth in the schools of Alameda County. Identification of the UE in the Fault Tree Analysis was: "Failure to be employed full time in an entry-level job with possibilities for advancement." (Witkin and Stephens, 1968, p. 25). The tree had eight distinct, but related branches with well over 700 failure events. The average depth of resolution was seven levels, with some branches extending to level twelve. A strategic path was calculated which revealed the most probable modes of occurrence within the system. Even a simple inspection of the tree provided very useful information about potential hazards which was of value to educational decision makers in vocational administration, curriculum development, etc. (Stephens, 1973).

The study resulted in many findings, the major ones of which indicated that the preparation for employment and the actual process of employment is more complex of a problem than is often assumed. The need for improvement of oral communication skills, individualizing instruction, formulating adequate objectives and teaching strategies, and correct assessment of student abilities was noted (Witkin and Stephens, 1968). Information gleaned from the tree was made available to educational planners for system redesign, proper allocation of resources, and planning for future needs. This initial attempt to apply the fault tree technique to education demonstrated the feasibility and value of Fault Tree Analysis in resolving some problems in vocational education (Stephens, 1972).

Since 1968, Witkin and Stephens have successfully applied Fault Tree Analysis to other problems in education. In 1972 application was made to organizational communication systems (Witkin and Stephens, 1972). In 1970 Stephens conducted a FTA of the Church of Jesus Christ of Latter-Day Saints Church Education System throughout the South Pacific (Stephens, Distinguished Lecture Series, Utah State University, 1974). In 1972 he devised a subjective quantification technique and since then has acted as a consultant in applying Fault Tree Analysis to many areas of education.

At present, the relatively few people skilled in Fault Tree Analysis limit its current use in education. Most of the current studies using FTA as a research tool have been undertaken at Brigham Young University and are of recent origin--largely due to the fact that Dr. Kent Stephens is presently affiliated with that university and is there teaching the technique.

During the 1974-75 school year, Collings (1975) conducted a Fault Tree Analysis of a high school recreation program in order to develop recommendations for teaching students how to effectively use their leisure time. The study was undertaken at two selected school districts in British Columbia, Canada. In developing inputs to the qualitative fault tree and in quantifying it, a committee of nine experts expended approximately 100 man-hours (Collings, 1975). In addition, Collings spent about another 150 man-hours in clarifying and rewriting inputs, preparing the quantitative data for computer processing, etc. The completed fault tree depicted 479 failure events. With one exception, all logic gates were OR gates. Four major divisions or branches of the tree were developed, varying in depth of resolution from three levels to nine levels. All failure events were secondary events (rectangle or rhombus) except for two houses and one circle.

Nelson (1976) conducted an extensive Fault Tree Analysis at the College of Eastern Utah to determine the cause and effect relationship which resulted in the college's failure to:

1. Provide educational opportunities which met basic academic needs of students.
2. Provide educational opportunities which serve student vocational needs.
3. Create an atmosphere which encouraged fulfillment of student social needs and development of a positive feeling of self worth.
4. Serve the professional needs of its personnel.
5. Serve the education needs of the Eastern Utah community.

Over 30 members of the faculty, staff, studentbody, and community were directly involved as committee members in qualitative fault tree development and quantitative evaluation. Approximately 500 man-hours were spent by the committee and 810 failure statements related to the mission and goals of the College of Eastern Utah were generated (Nelson, 1976).

During the 1975-76 school year, Long (1976) applied FTA as a research tool to identify and prioritize internal communication failures within the community college district throughout the Ventura County Community College District, Ventura, California. Long selected nine committee members from among key management personnel of the local community college district with a combined total of 69 years experience in community college administration. A total of approximately 150 man-hours were expended by the committee in performing qualitative fault tree development and in quantification. An additional estimate of 100 man-hours was spent by the analyst in rewriting input failure statements, preparing data for quantification, etc. The completed tree had 474 failure events. All logic gates connecting failure events were OR gates. Three separate branches of the tree were developed.

Copeland (1976) has most recently conducted a Fault Tree Analysis in the Department of Physical Education at Brigham Young University, Provo, Utah to identify possible problem areas within that department. A committee of faculty members and graduate students assisted in the qualitative development and quantification of a fault tree made up of 133 possible failure causing events.

EXAMPLE OF A FAULT TREE ANALYSIS

In this section an example of a mission analysis and the qualitative construction of a fault tree is presented. Although the fault tree presented in this example was drawn specifically for use in religious education, it is useful as a prototype and to a degree can be used as a general model. The tree should not necessarily be construed as representing the final drawing. It could, if desired, be developed further and in some cases altered. The analysis of the prototype fault tree has been undertaken only to the extent of drawing the tree and verifying the inputs (validation). Quantification of the tree requires a probability evaluation which is beyond the scope of this paper. The fault tree, herein described, is displayed in the appendix of this paper.

Problem Identification

The Church of Jesus Christ of Latter-day Saints (L.D.S.) operates a released time religious education program (where enrollment warrants and local laws permit) throughout several western states (Utah, Arizona, Idaho, New Mexico, and Wyoming). Students participating in the program are released from their regular public school classes for approximately one hour each school day to attend seminary, where, in a religious setting L.D.S. Gospel precepts are taught. Besides daily class instruction, numerous after school activities and extra-curricular activities are available for interested students. These activities are generally under the direction of specified students selected by the seminary faculty to serve as seminary officers or student leaders. It was the desire of the author to assist in the development and administration of an effective student leadership program for use in small, released time L.D.S. seminaries.

A systems definition was undertaken and bounds and constraints were identified so as to limit the student leadership program for use in released time L.D.S. seminaries with an enrollment of 250 students or less, staffed by one or two teachers which would promote friendship among students, instill a desire for students to learn the Gospel, and provide opportunities for students to have spiritual experiences. The exact mission statement read: "Development and administration of a student leadership program in released-time seminaries, staffed by one or two teachers, which will promote within each student enrolled in class a feeling of acceptance by peers, a desire to understand the Gospel, and an opportunity to feel the influence of the Spirit."

Based on the mission statement and system definition, a mission analysis (see Appendix, Figure 9) was performed which identified five basic functions and 18 distinct tasks.

In viewing the mission analysis, several undesired events were considered and it was decided that the UE would be: "Failure to develop and administer a student leadership program in released time L.D.S. seminaries staffed by one or two teachers which will promote within each student enrolled a feeling of acceptance by peers, a desire to understand the Gospel, and an opportunity to feel the influence of the Spirit." In this particular case the UE happened to be the reciprocal of the mission statement.

Qualitative Fault Tree Construction

Qualitative fault tree construction was begun by scoping the initial levels of the tree derived from the mission analysis.

Most of the events depicted in the fault tree in this paper are secondary (rectangle or rhombus) failure events. The tree has five separate branches and levels of development for any single path range from two levels to six. The completed tree has 141 failure events.

The actual generation of the inputs in the qualitative development of the tree was undertaken chiefly by the author with some assistance from the seminary principal at Bountiful-Millcreek Seminary, Bountiful, Utah and the district coordinator of the Davis County Seminary District. The "Systematic Five Step Approach to Qualitative Fault Tree Development" suggested by Stephens (Class Lecture, November 11, 1975) was utilized in formulating failure statements for use in development of the tree. Approximately ten hours was expended in formulating inputs (failure statements) and another eight hours in clarifying the statements and actually drawing the tree. The inter-relationship of failure events in the tree are depicted only by the OR logic gate. The AND logic gate is not used in this fault tree.

Recommendations

The entire process of quantification was not undertaken for the prototype fault tree. The tree was inspected thoroughly by the seminary principal, district coordinator, and the author and at some levels events were ranked against each other. Although numerous suggestions evolved from the inspection of the tree, the following were among the major needed recommendations:

1. It was agreed that a written job description be made available for each student officer listing his specific duties as well as those of other officers.
2. It was agreed that student leaders be in charge of and delegate authority to contact and commit peers to attend morningsides (inspirational meetings), testimony meetings, and other student activities.
3. It was determined that a regularly scheduled weekly meeting (specifying time and place) was necessary between student leaders and teachers to coordinate activities.
4. Student leaders were given responsibility to assist in motivating peers to keep current in assigned class reading.
5. Student leaders were placed in charge of classroom devotionals, being able to receive assistance from the teacher if desired.

CONCLUSION

In October of 1968, Witkin and Stephens (p. 42) wrote:

> At the point to which fault tree analysis has now been developed for educational problems, it is not possible to predict its ultimate usefulness to educational planners. Certainly, the state of the art is not yet at the point where its full potential can be unequivocally demonstrated.

Ten years has seen considerable development of the fault tree process, largely due to the work of Stephens in devising a subjective quantification technique. Although the relatively few persons skilled in educational FTA presently limits its application, the efforts of Stephens and others in teaching the technique will certainly have a mushrooming effect as time goes on.

Fault Tree Analysis is not seen as a panacea for use in the systems approach, nor is it necessarily a replacement for other forms of systems analysis. Its effectiveness stems from its focus on "how things can fail to work" and from this perspective it is of great value, for it leads to explicit recognition of possibilities for trouble which might otherwise be overlooked.

Ultimately, the value of Fault Tree Analysis lies in its potential for accurately identifying those failure modes within a system which, if prevented or minimized will increase the probability of success of the system. The suggestion is not intended that mere avoidance of identifiable failure modes will guarantee success, but it definitely can promote success.

One factor which can considerably facilitate the use of FTA is that it can be applied as a most simple or a most sophisticated analytical tool, depending on the needs of the analyst. The concepts of Fault Tree Analysis are outstandingly simple, however, constructing suitable fault trees--especially for complex educational systems--requires thorough understanding of the system being analyzed (or immediate access to individuals who do) as well as a mastery, at least for the analyst, of the techniques of fault tree construction. Team members assisting in an analysis need only understand the rudiments of Fault Tree Analysis. Undoubtedly, the future of FTA in education will depend largely on the number of individuals trained in the technology, who also possess an ability to adapt it to pertinent problems in education.

One final note. In the opinion of the author, it is a wise administrator who designs processes which enable decisions to be made by others and does not make all the decisions himself. He permits people, within limits, to choose for themselves. Fault Tree Analysis does not say, "Do these things and you will be successful." Rather, by identifying what not to do it seems to be proclaiming, "You are free to determine the avenue which is most suitable for you to achieve success, however, these strategies should be avoided in order to enhance the possibilities for success." In a Biblical context, FTA declares, "Thou mayest choose for thyself, for it is given thee; but it is intended that thou shalt not fail!"

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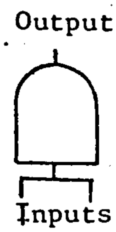
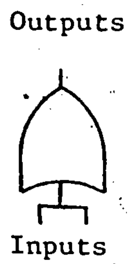
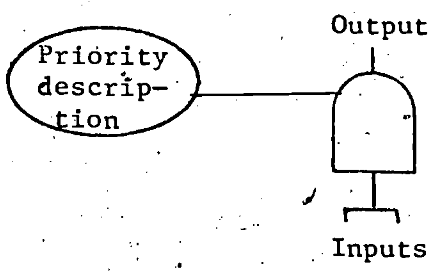
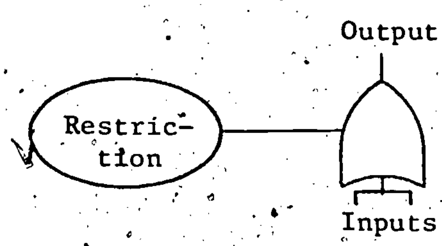
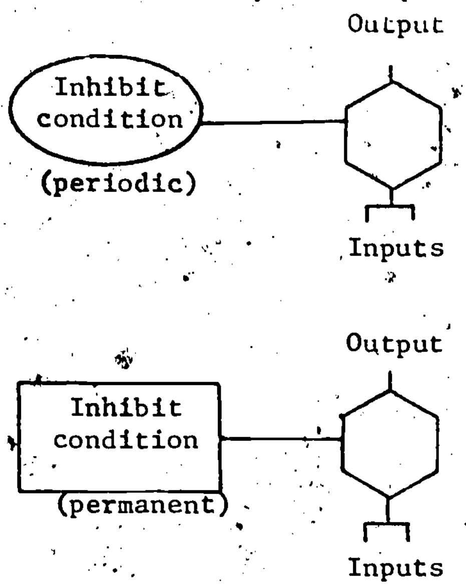
APPENDIX

Glossary: Logic Gates

Gate Symbol	Definition:
	The AND Gate describes the logical operation whereby the coexistence of all input events is required to produce the output event.
	The OR Gate defines the situation whereby the output event will exist if one or more of the input events exists.
	The PRIORITY AND Gate performs the same logic function as the AND Gate with the additional stipulation that sequence as well as coexistence is required.
	The EXCLUSIVE OR Gate functions as an OR Gate with the restrictions that specified inputs cannot coexist.

Gate Symbol



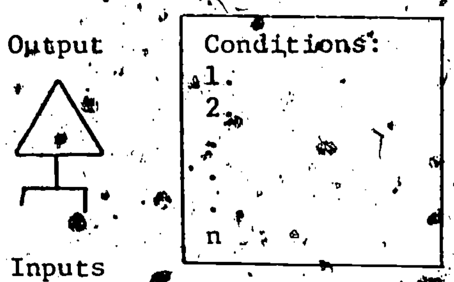
Definition:

INHIBIT Gates are AND Gates in which one of the inputs occurs with enough consistancy to inhibit the other inputs. The other input events directly produce the output event if the indicated condition is satisfied or occurs. The condition is represented by an oval if it describes a specific failure mode and a rectangle if it describes a condition that may exist for the life of the system.

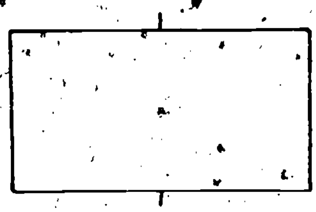
(Stephens, 1973, p. 34)

Fault Events

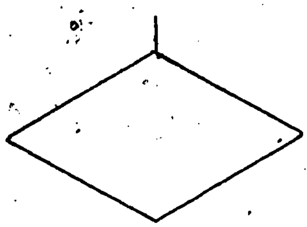
Event Symbol | Definition:



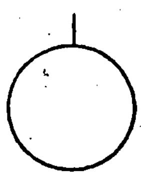
The MATRIX Gate is an abbreviated representation of a combination of events, which can be represented by a series of AND Gates summed together by an OR Gate, in which some of the inputs are common among the different AND Gates.



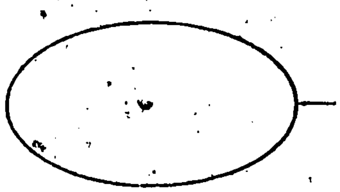
The RECTANGLE identifies an event that results from the combination of fault events through the input logic gate or for which additional fault tree development exists. The event is an input to the logic gate above the rectangle.



The RHOMBUS describes a fault event which is not developed further in the tree, because (a) the necessary information is unavailable, (b) the event is relatively unlikely, or (c) time, technology, or other constraints preclude analysis to further depth.



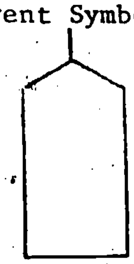
The CIRCLE describes a basic fault event that requires no further development. It is a primary failure of a discrete element due to its internal conditions.



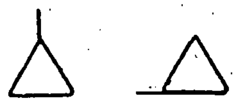
The OVAL specifies conditions among inputs to logic gates. It defines the state of the system that permits a fault sequence to occur, and may be either normal to the system or result from peculiarities among failures.

Event Symbol

Definitions:



The HOUSE indicates an event that is normally expected to occur, such as a phase change or periodic surge of events in a dynamic system. It is a basic input, requiring no further analysis.



The small TRIANGLES are used as transfer symbols when parts of the tree are transferred to another page or section of a page. A line from the apex of the triangle indicates a "transfer in" and a line from the side denotes a "transfer out," of a portion of a fault tree.

(Stephens, 1973, p. 35)

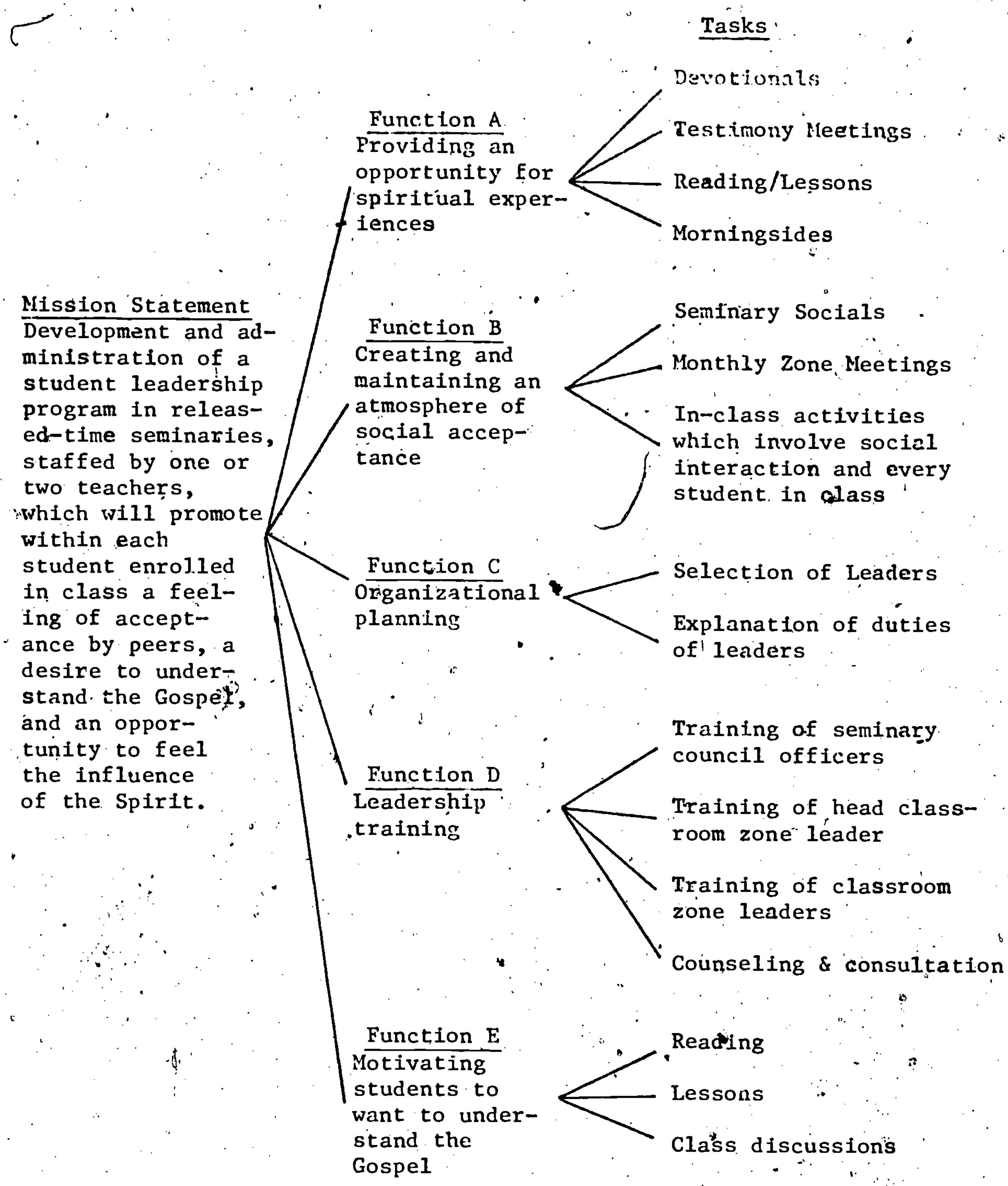


Figure 9. Mission analysis prototype fault tree

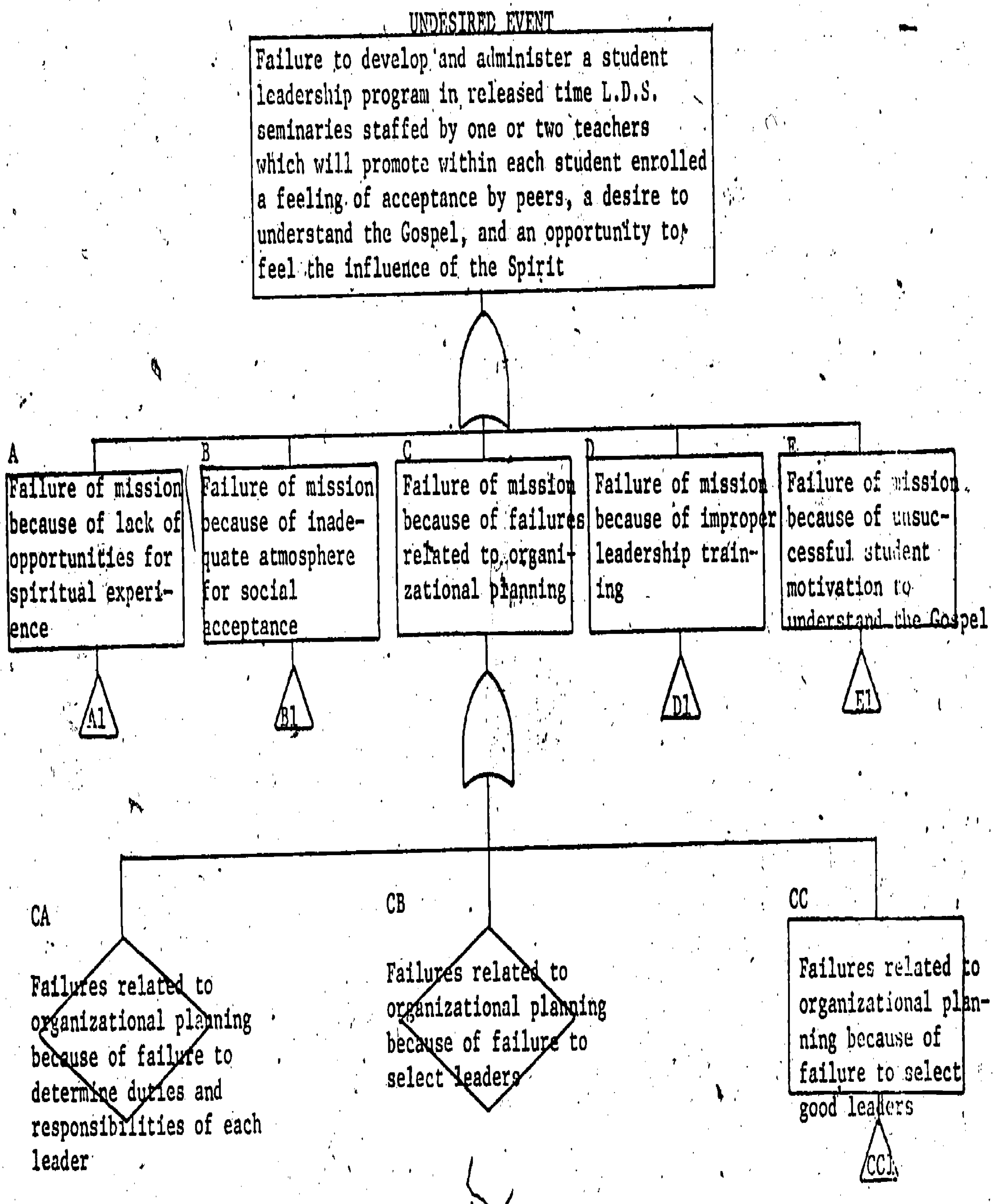


Figure 10. Prototype fault tree.

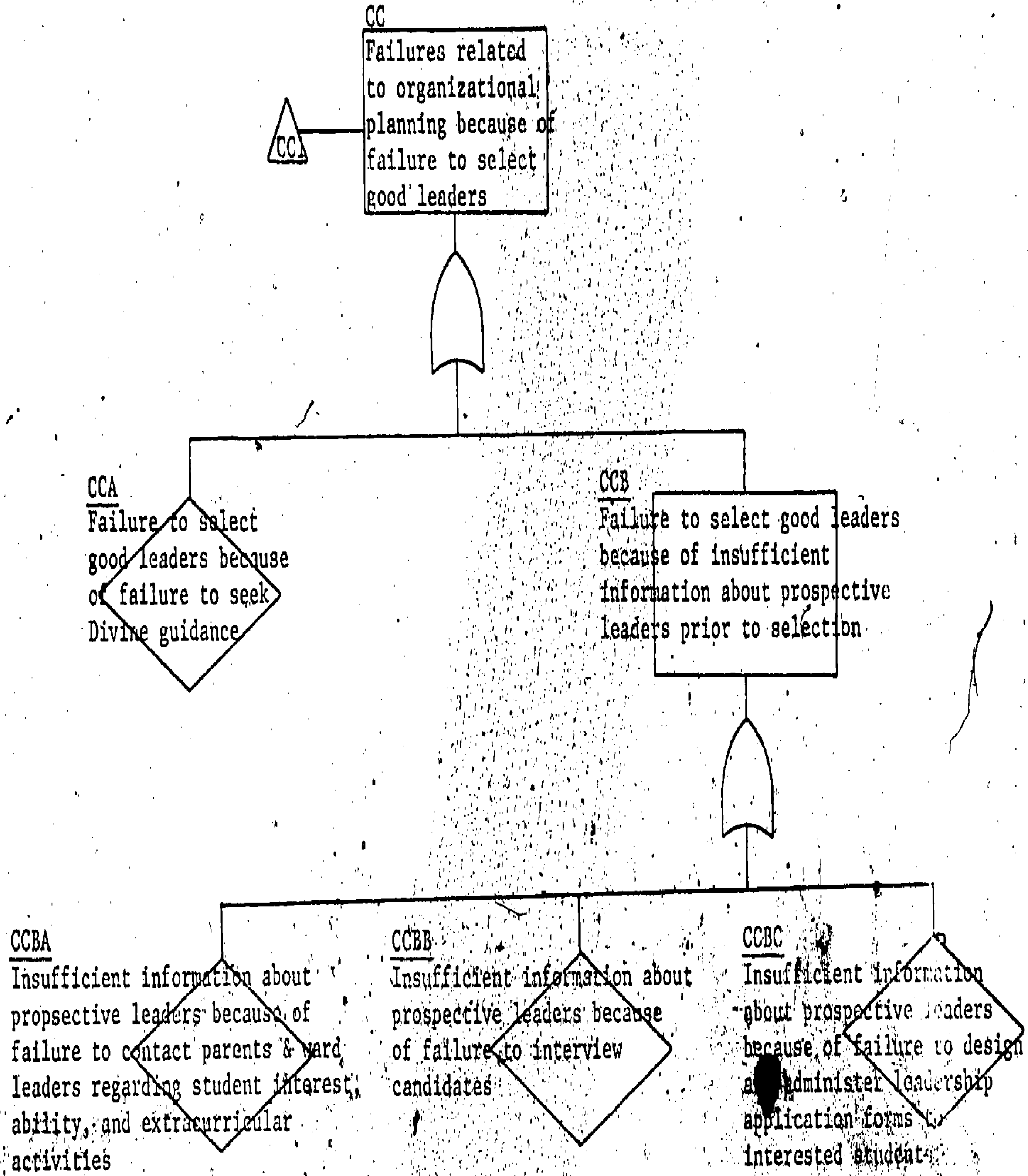


Figure 10. Continued.

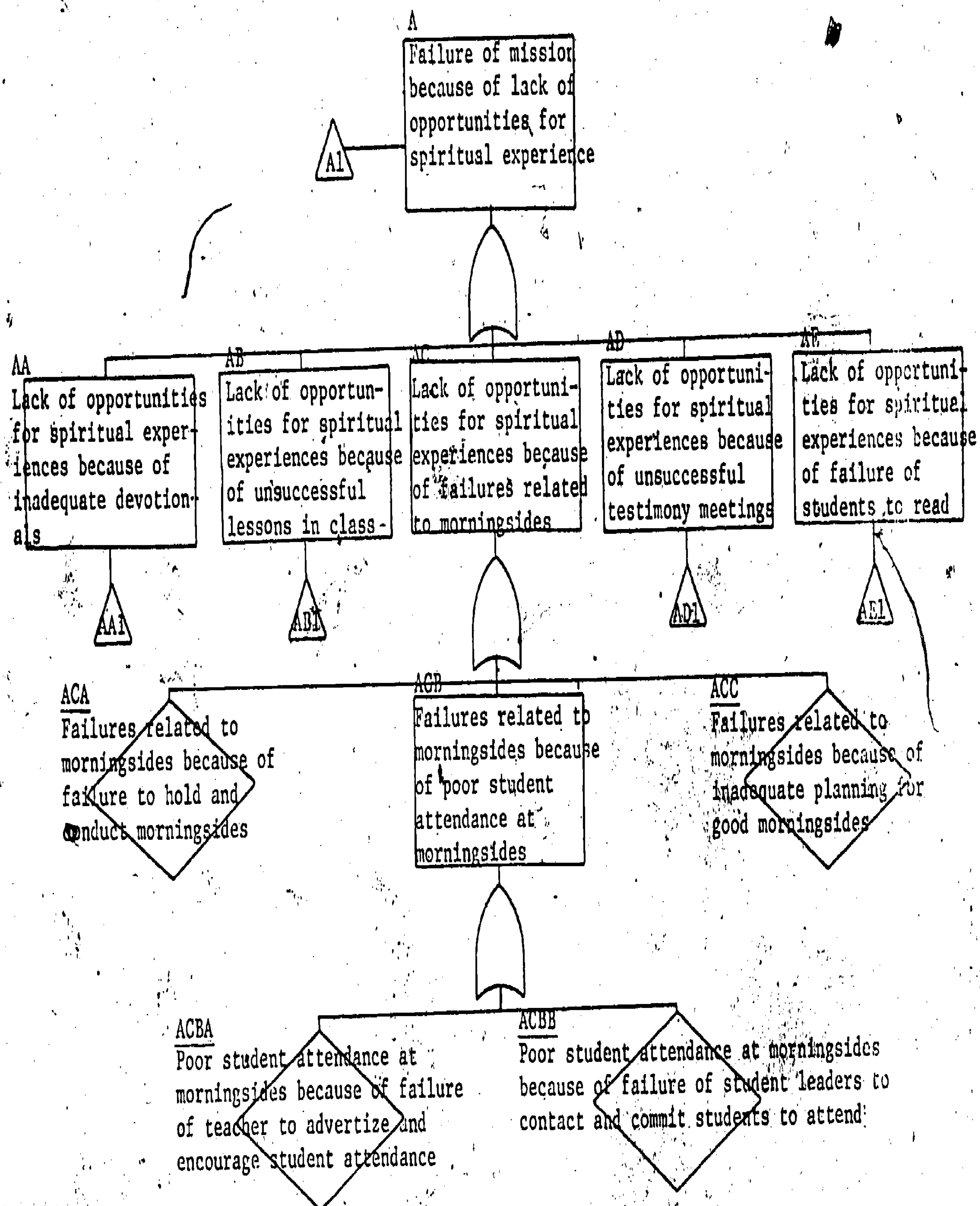


Figure 10. Continued.

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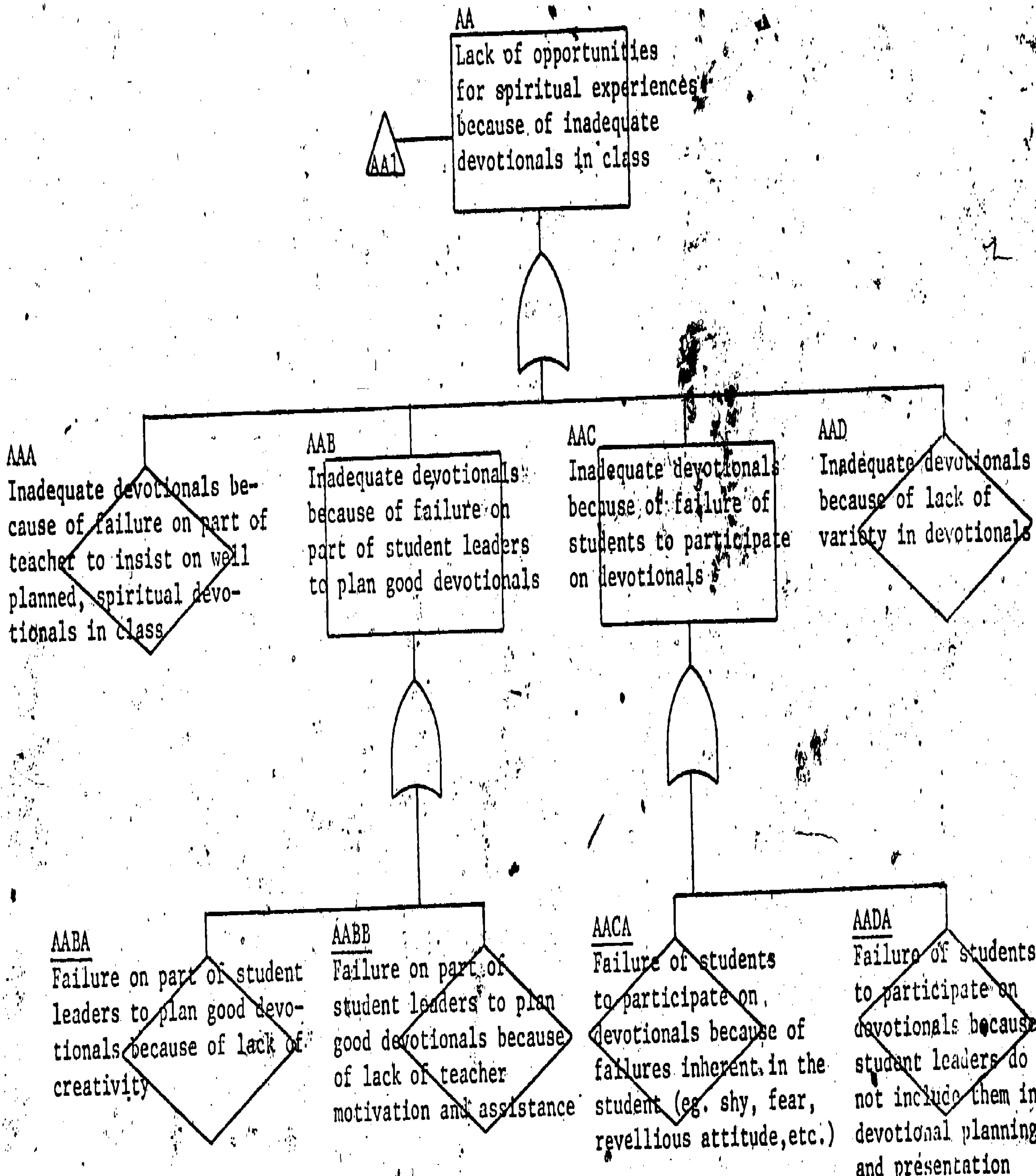

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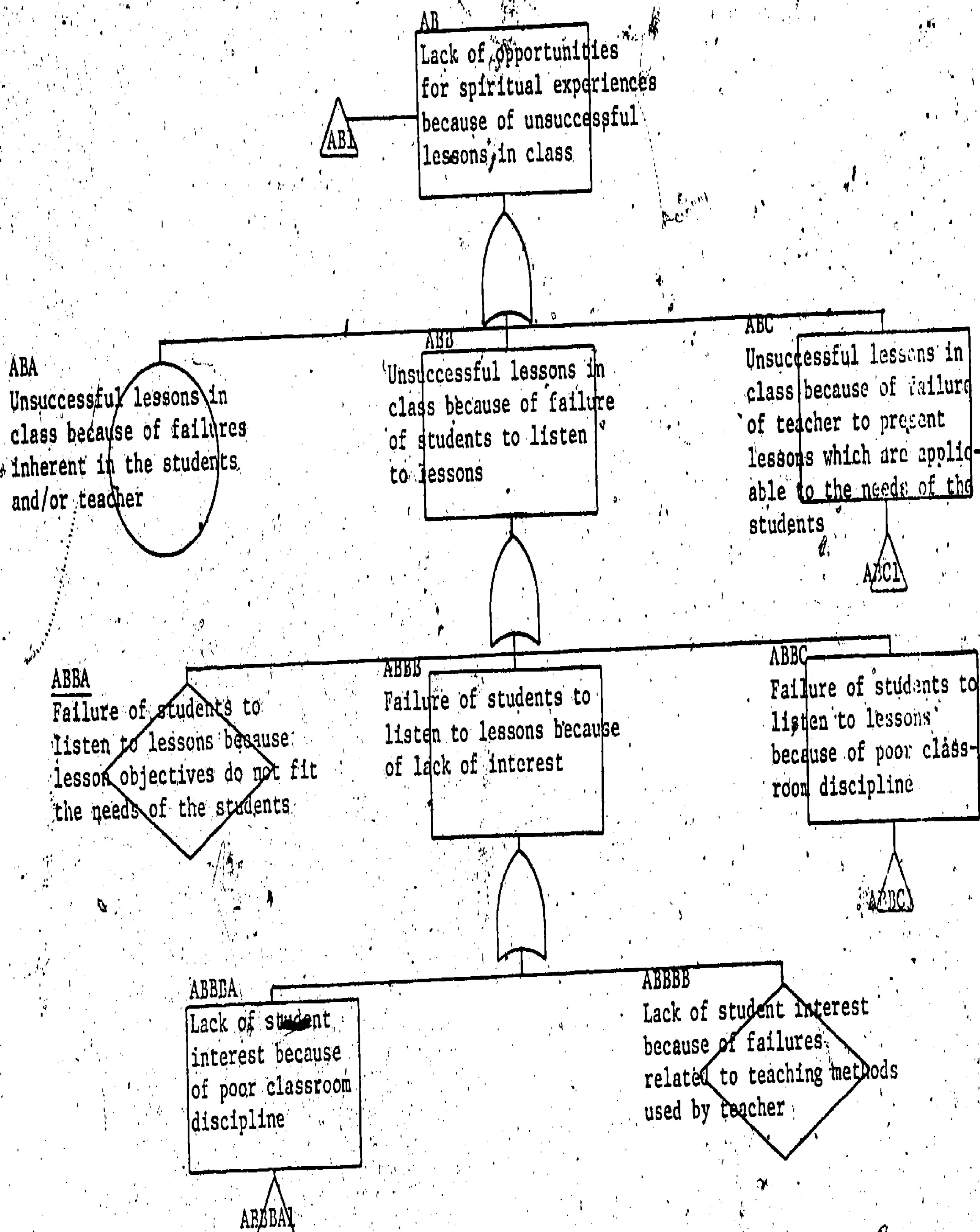

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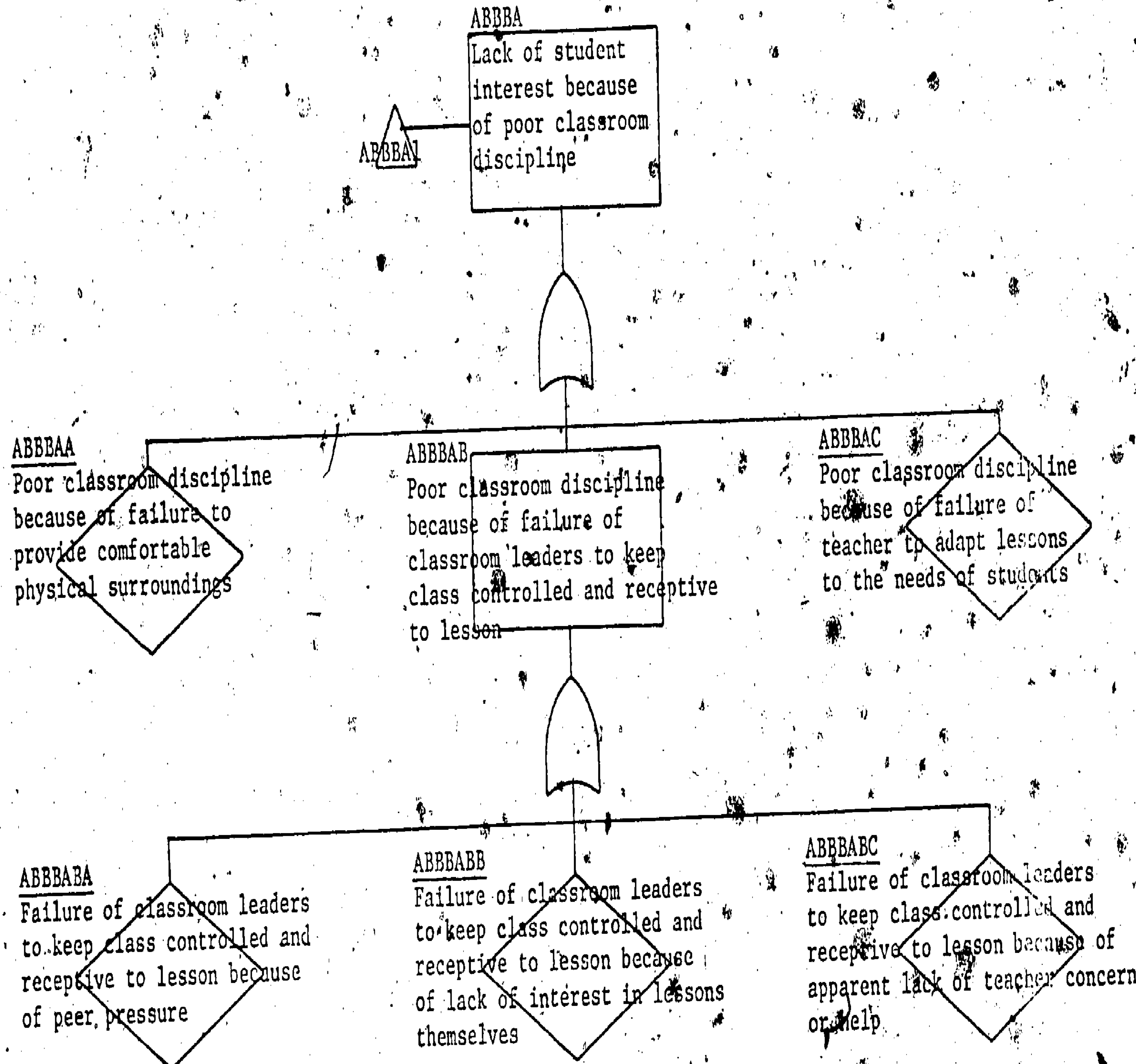
57



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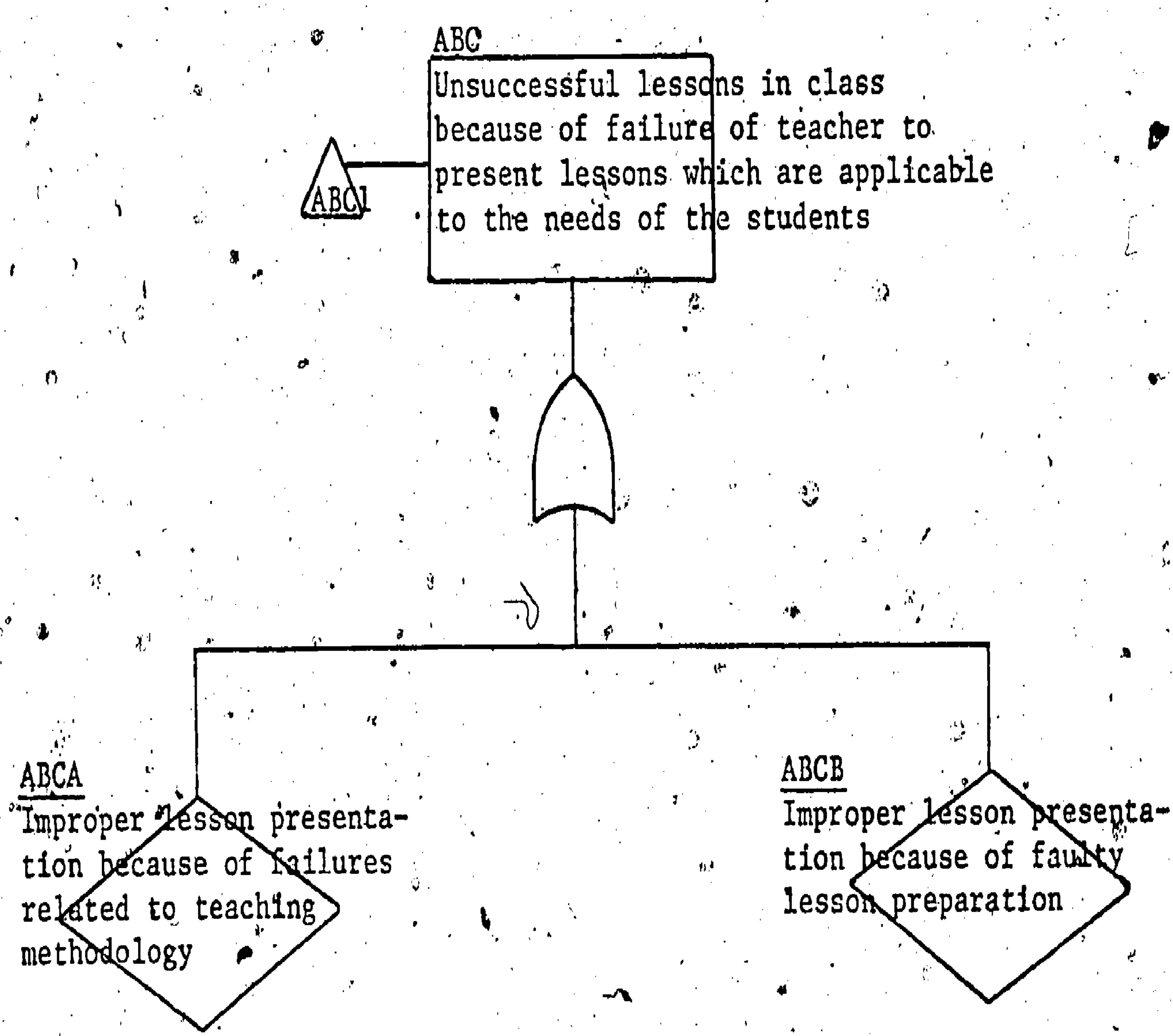

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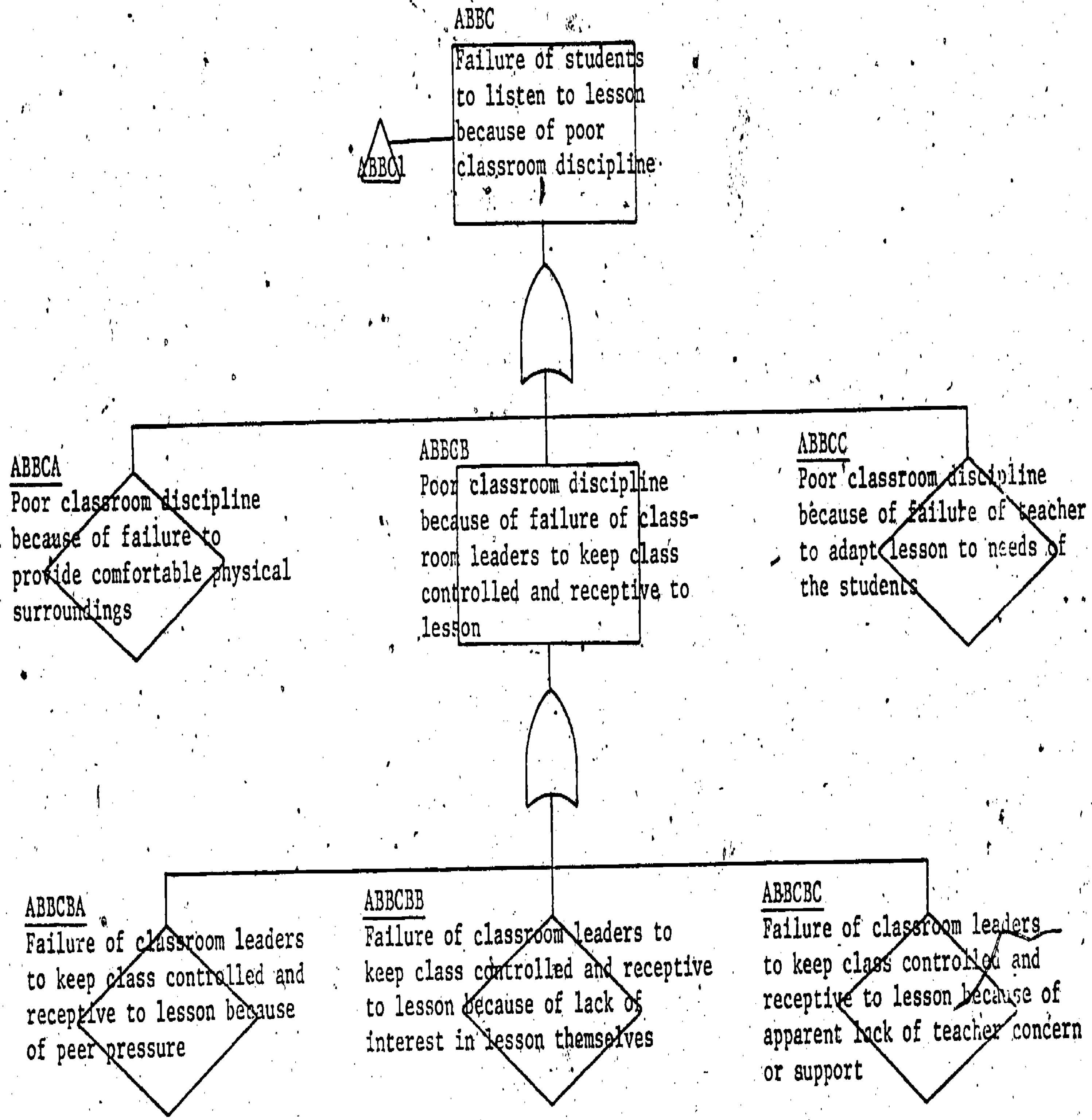

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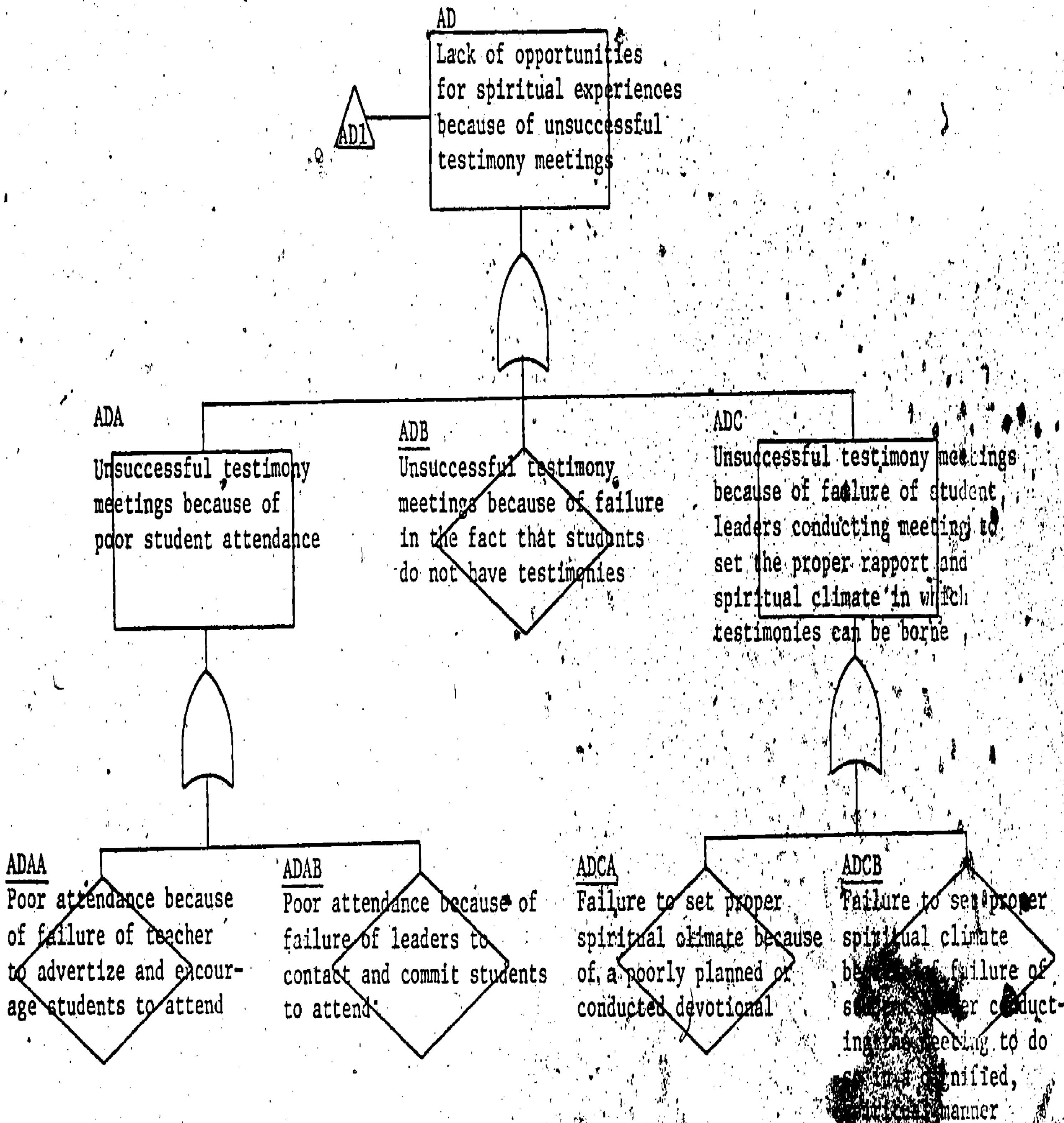

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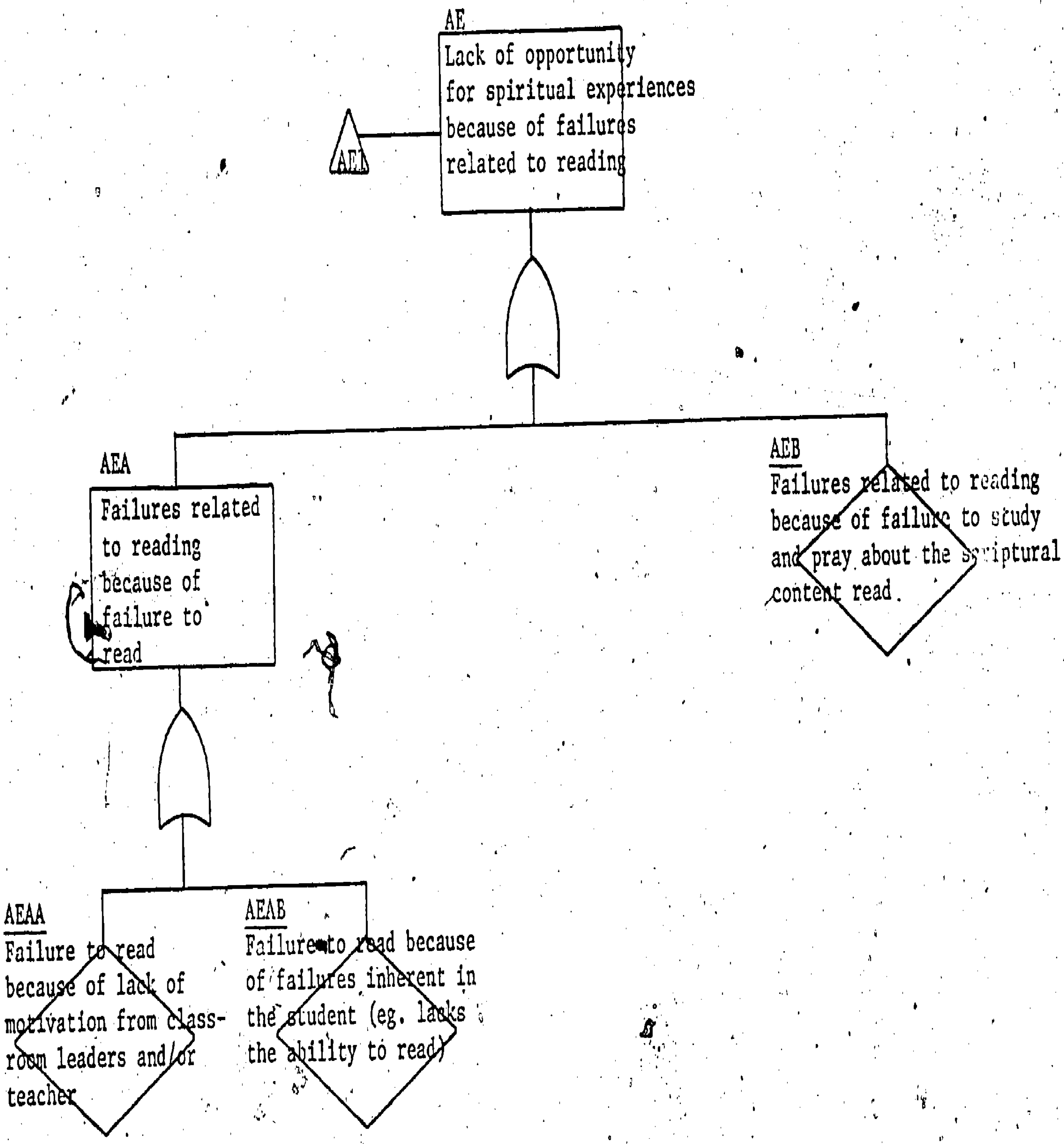

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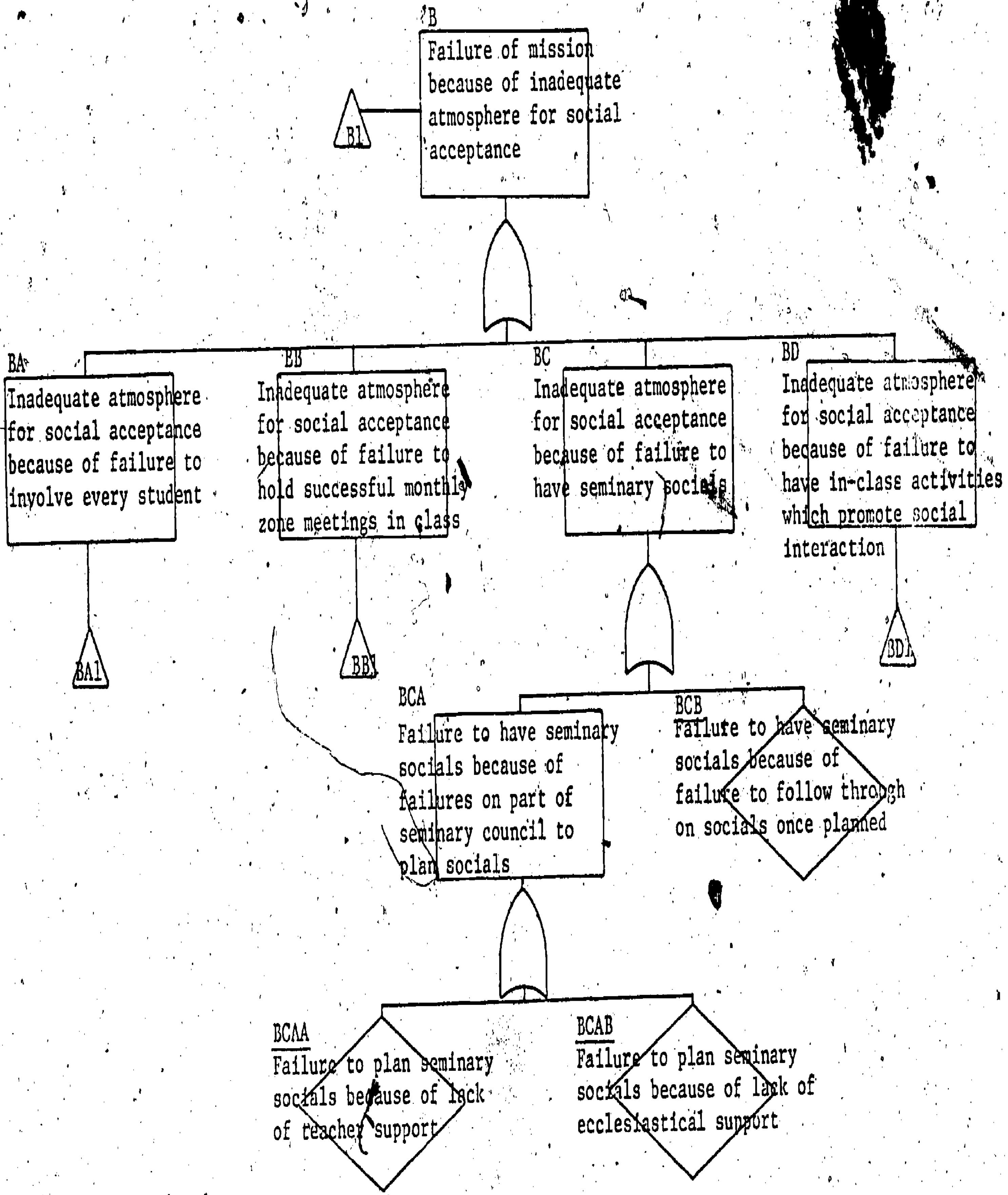

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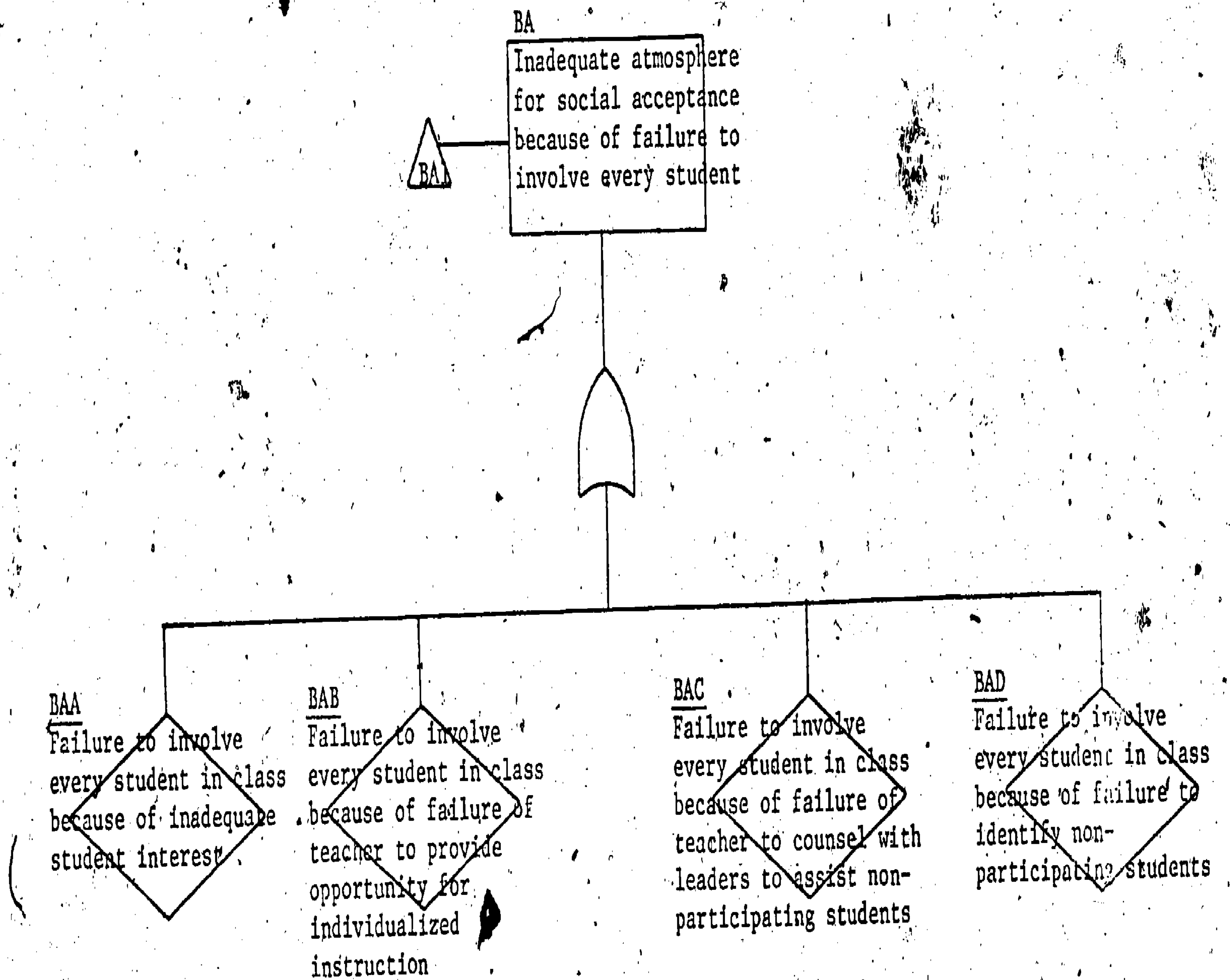

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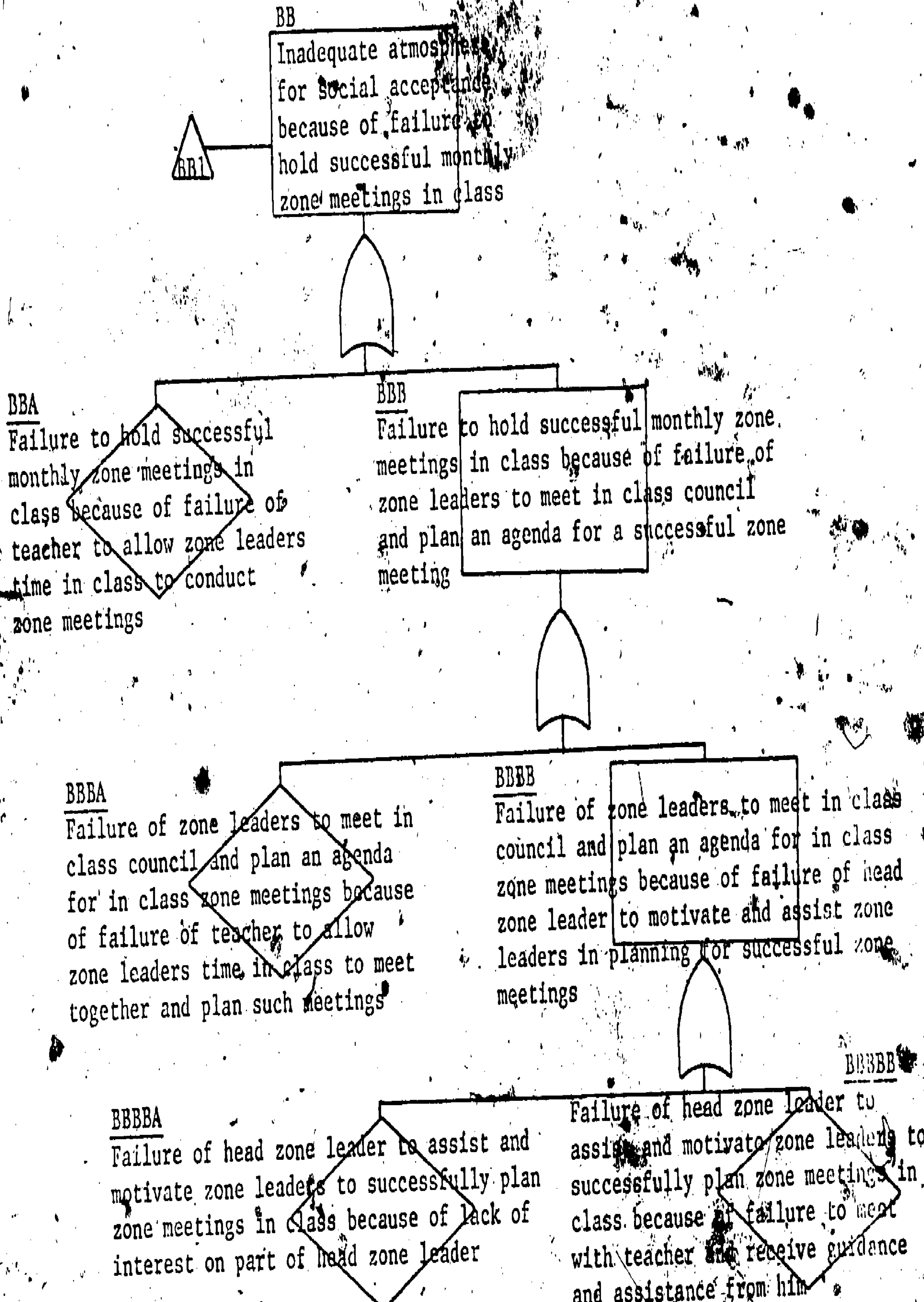

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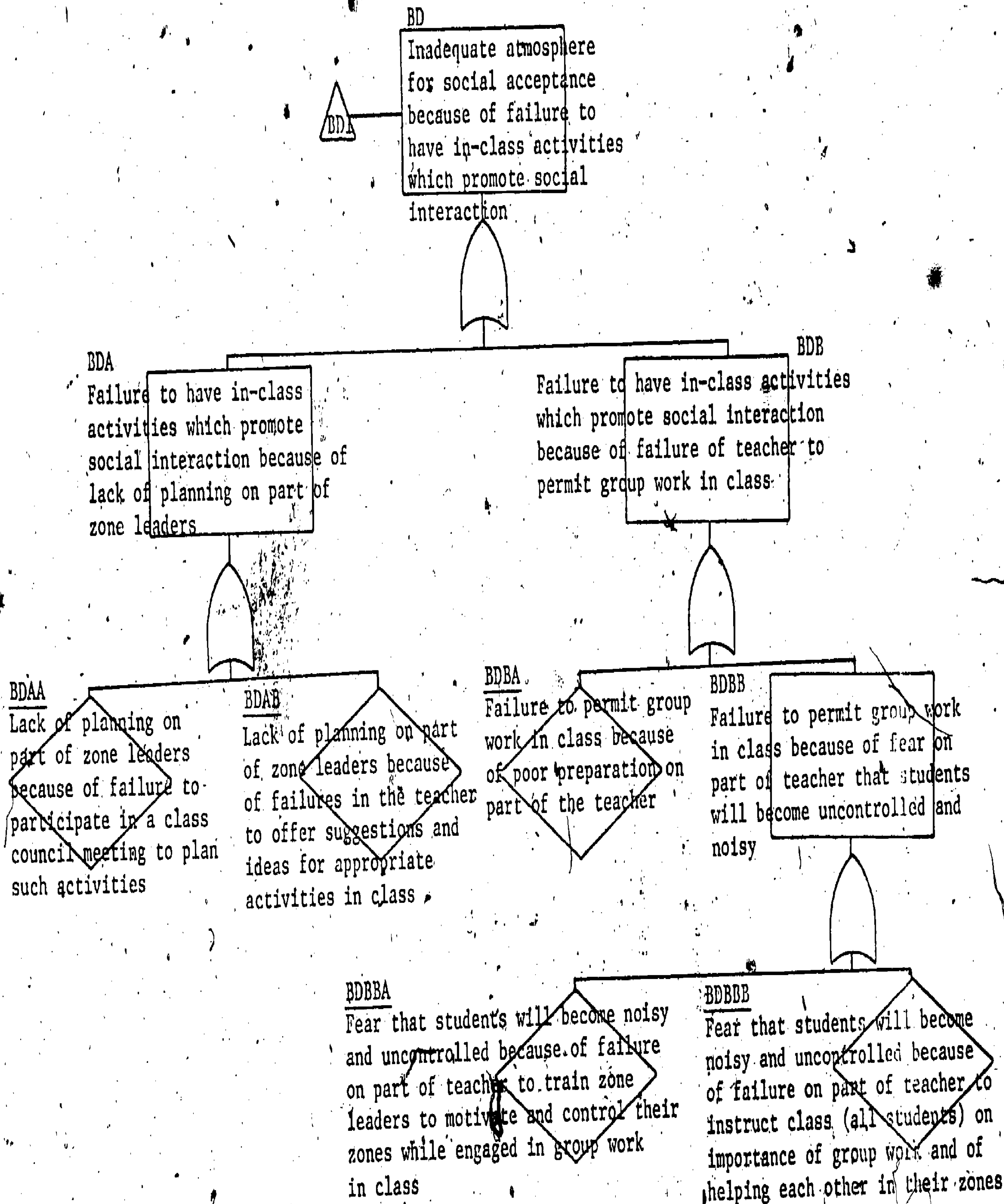

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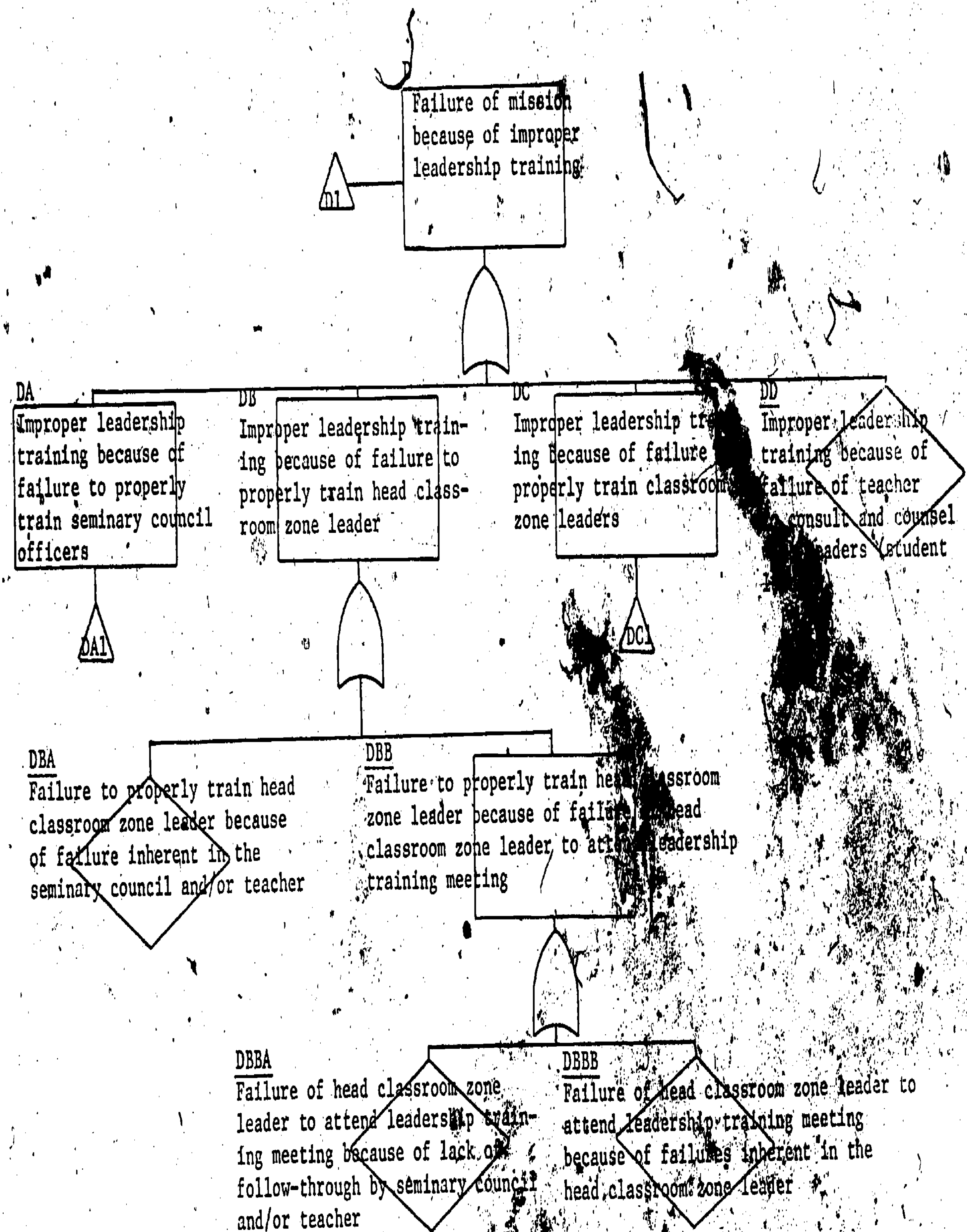

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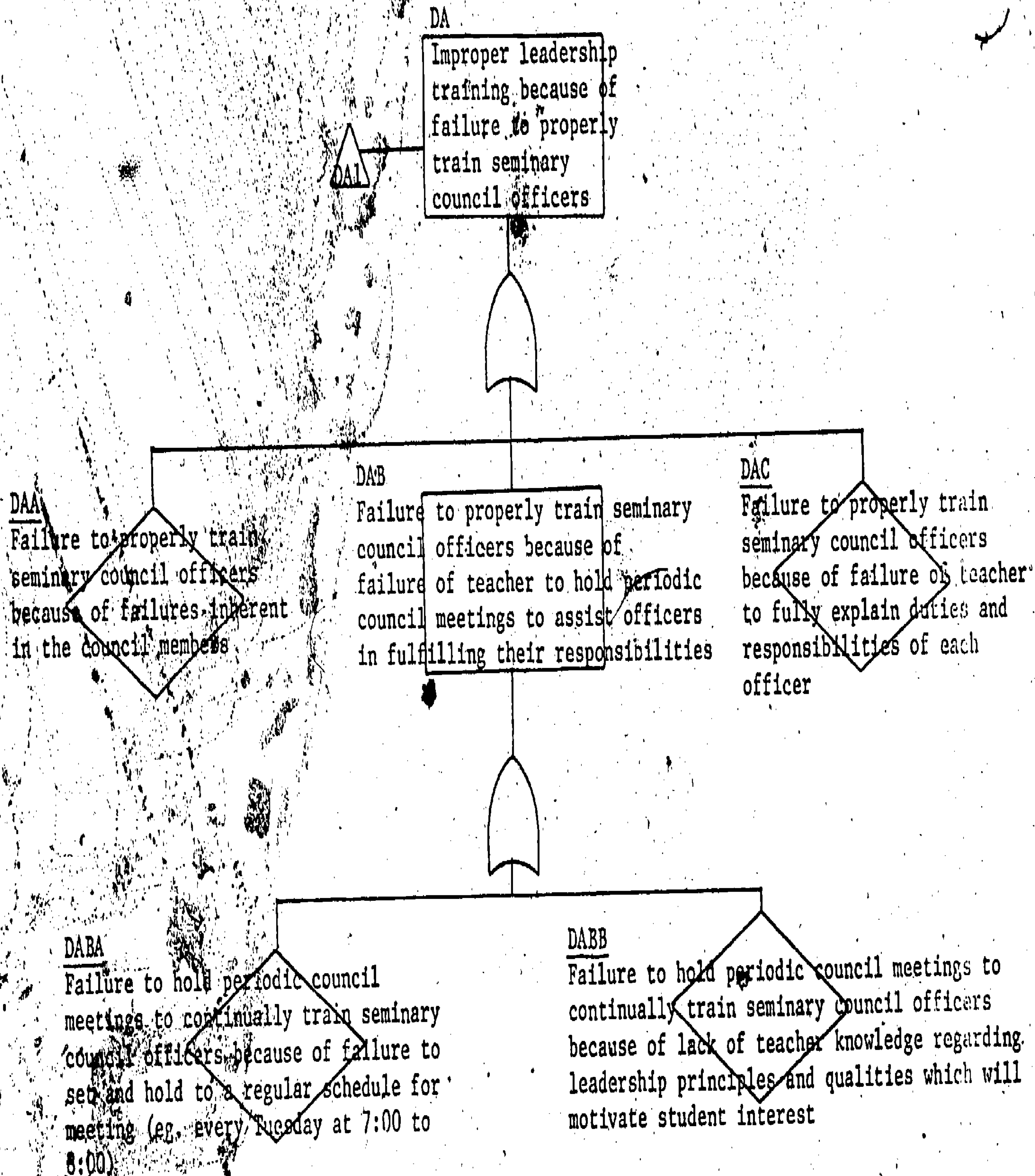

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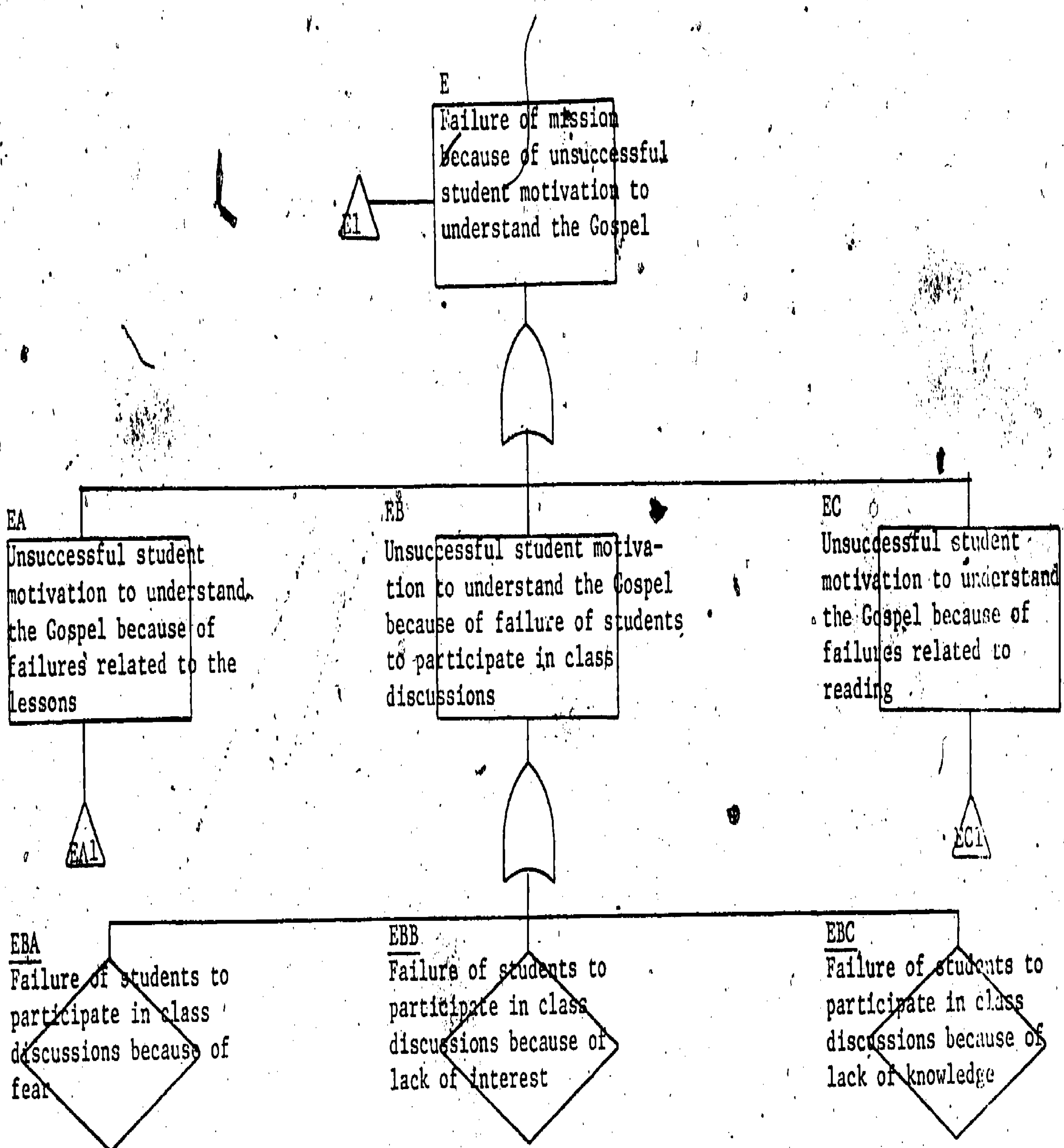

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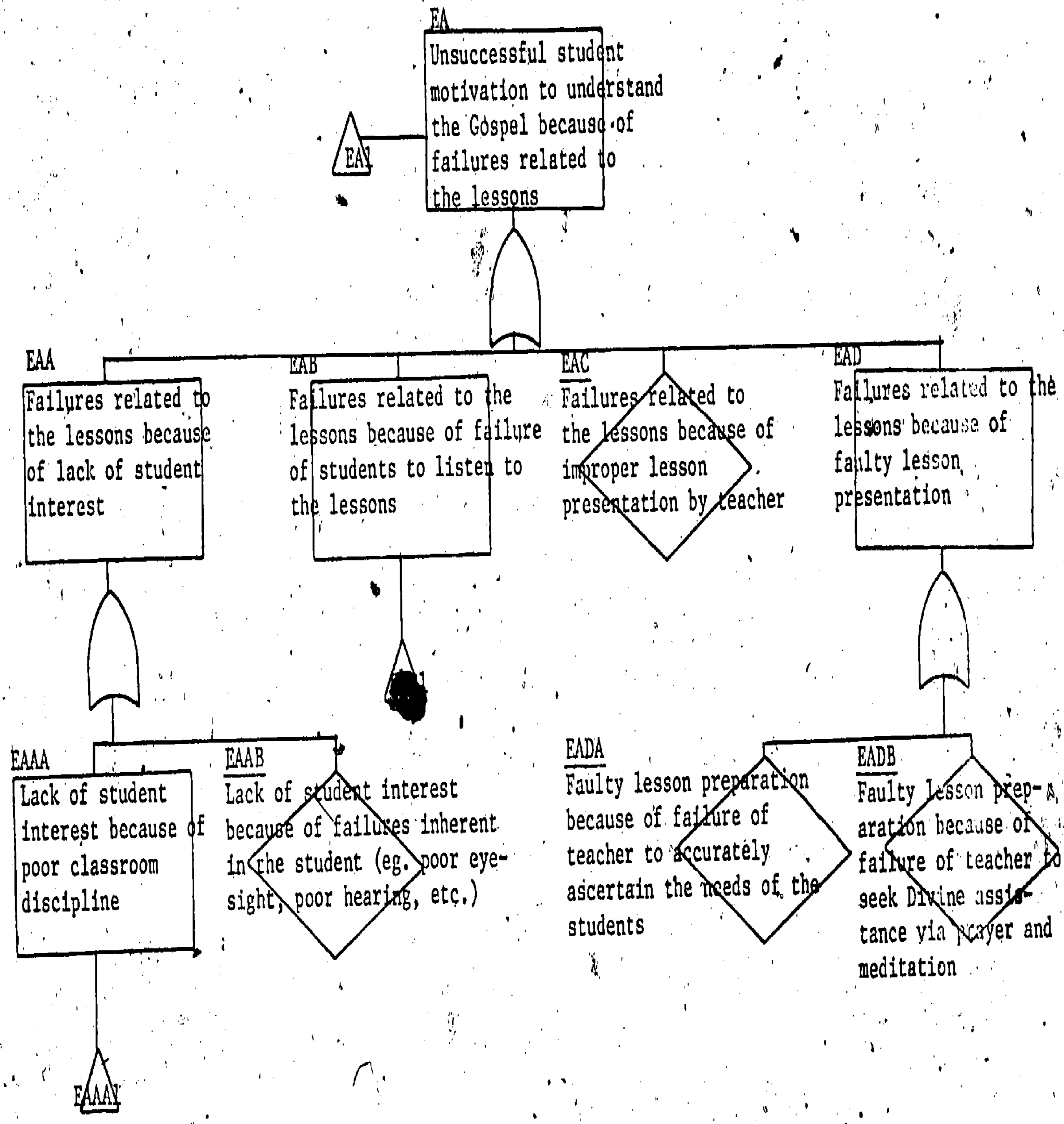

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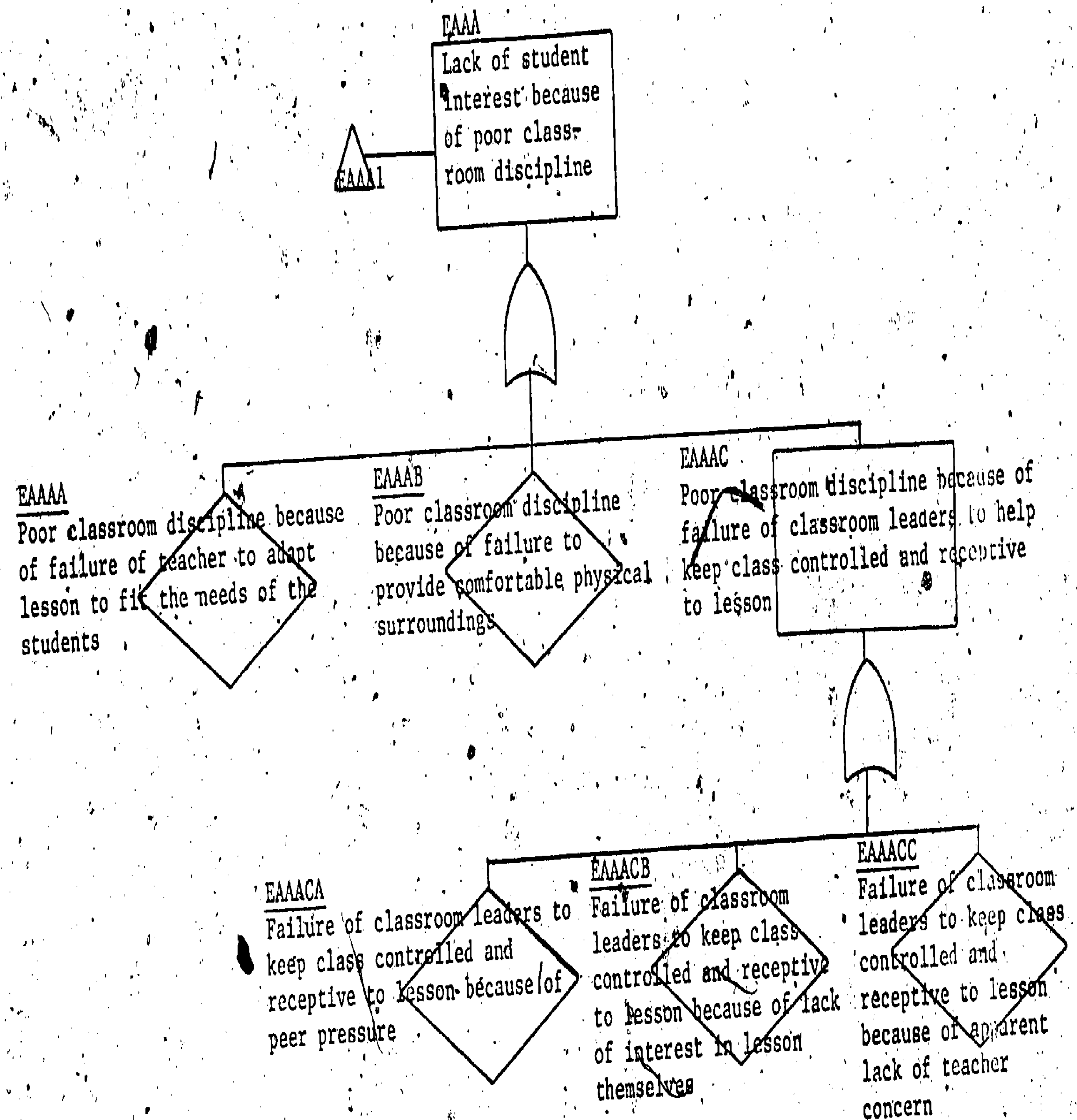

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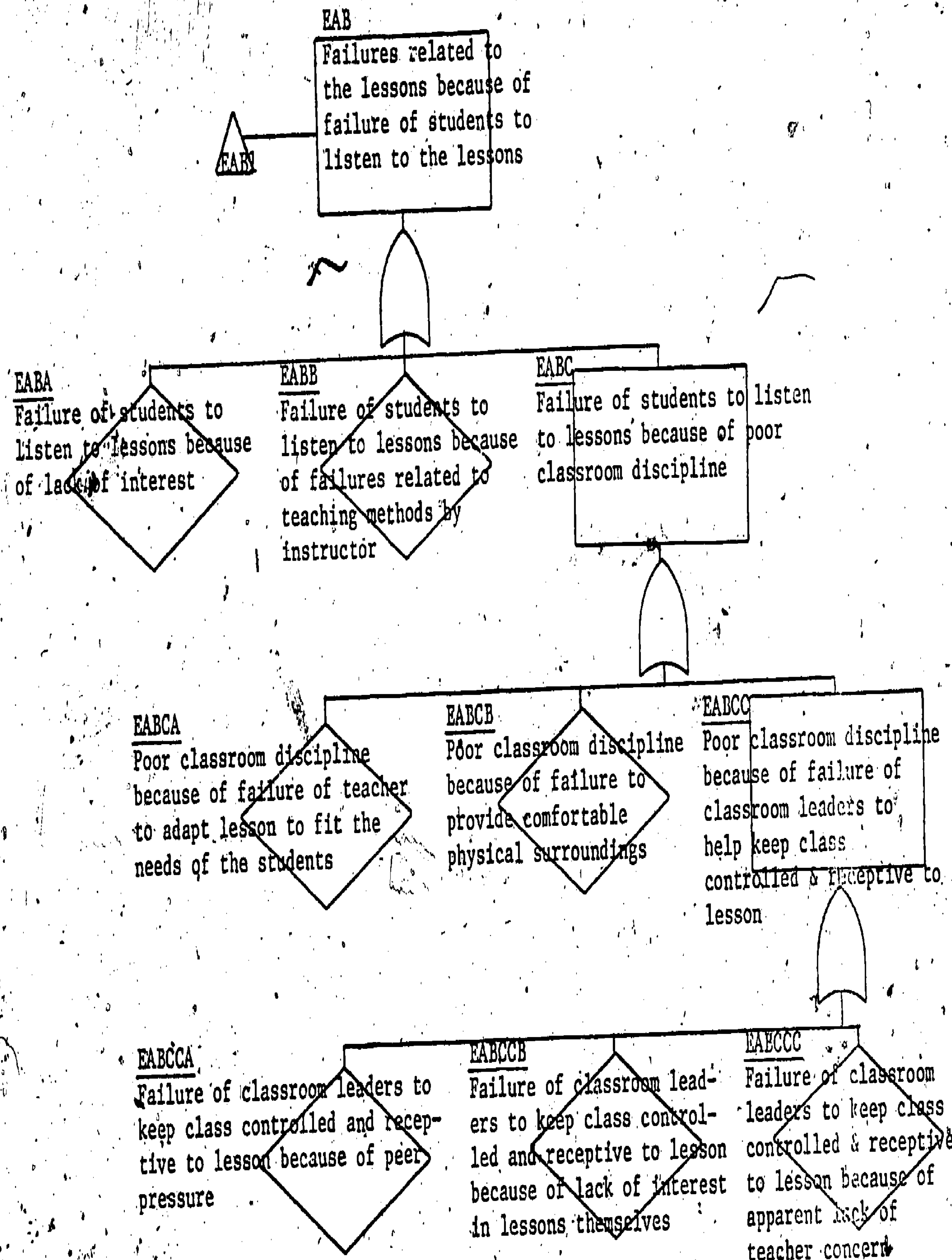

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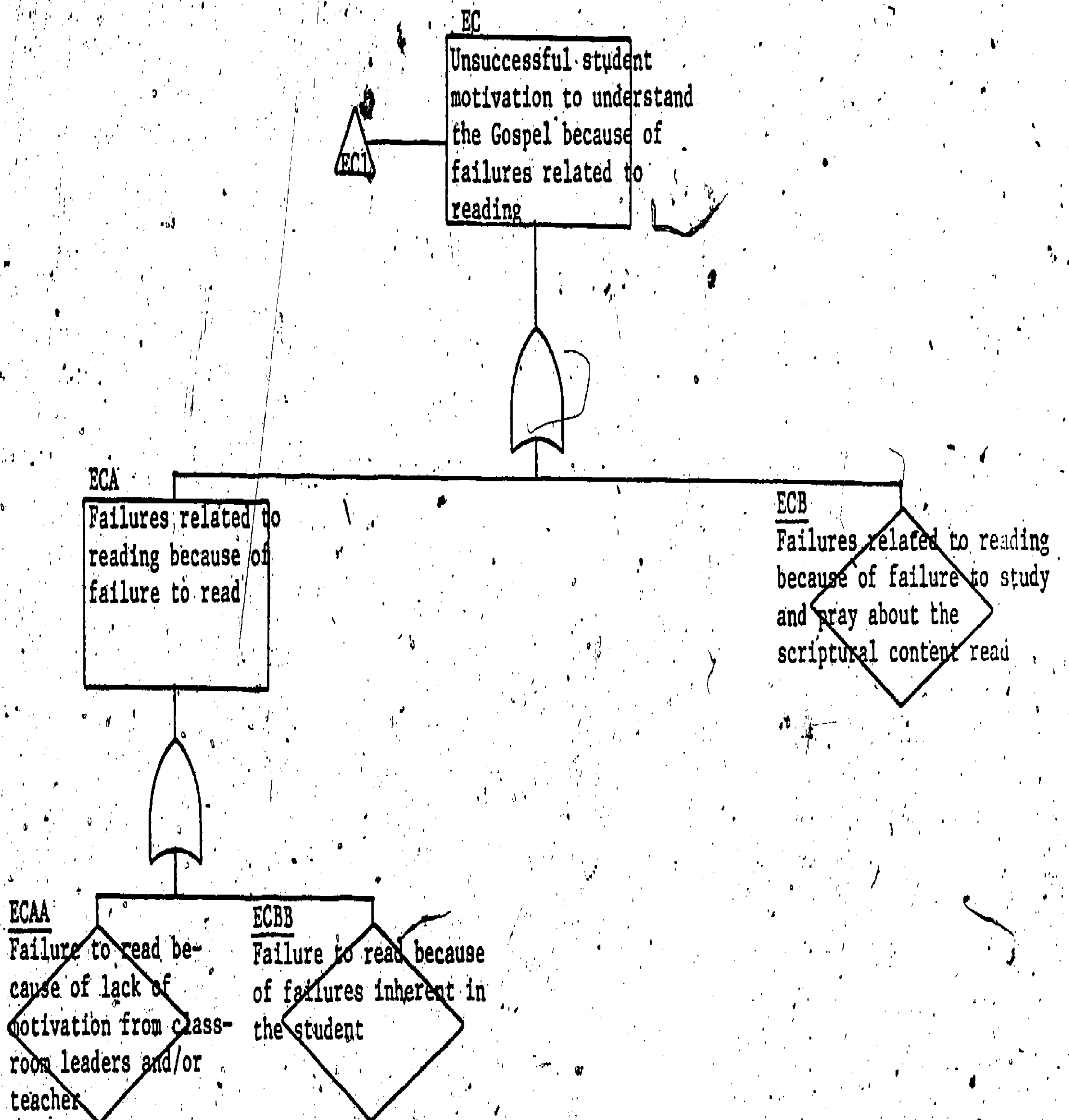

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