An Expert System for Predicting Radiated EMI from PCB's

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Abstract: This paper describes an expert systems approach, based on symbolic reasoning techniques, to the problem of predicting radiated EMI levels from printed circuit boards. The expert system, currently under development at the University of Missouri-Rolla, starts by extracting board geometry information from the board layout files. This information is fed into the *classification algorithm*, which determines the signal properties and nature of each net, using the knowledge stored in the *knowledge base*. The *evaluation algorithm* uses the available information to identify and evaluate critical circuit geometries, and then estimates the effect that these geometries have on system radiation levels. The expert system also looks for violations of basic EMC design rules. The main advantage of such a system over conventional software is that the expert system does not require the user to be an expert in EMC or circuit design.

Introduction

Software tools that calculate radiated fields from electronic systems are notoriously difficult to use, and do a poor job of estimating radiated emission levels. This is partly because it is not practical to enter into a computer all the information about a system that plays a role in the radiated EMI levels. It is also due to the fact that EMI tests are not very repeatable [1], and details such as cable placement and how tightly a cover is screwed on can have a major effect on the measured field strengths. So, given that most EMI software tools are trying to predict the results of an ill-defined measurement using incomplete information, it is not surprising that they are not more effective.

It is tempting to conclude that EMI sources are too complex, and that the EMI problem is just too difficult to solve. However, a person experienced in EMC can generally examine a printed circuit board design and (with enough information) make a reasonable estimate of how well that design will do in an EMI test. Although the expert's estimate will not be perfect, it will often be quite close and the information gleaned from the expert's analysis of the design can be an invaluable aid to help reduce radiated emissions.

Why can't EMI software make an estimate that is as accurate as that of an experienced expert in EMC? The answer is that it can, but not by doing exhaustive numerical field calculations. To be effective, EMI software has to take an approach similar to that of the human EMC expert. An *expert system* approach to the modeling of printed circuit boards is described in the following sections. This approach uses symbolic reasoning techniques to model the thinking process of an human EMC expert. *EMC expert system* software can predict radiated EMI levels, locate and evaluate potential EMC problems, and suggest changes in a design that will alleviate those problems.

Expert Systems

The concept of expert systems originated from research in artificial intelligence (AI), a subfield of computer science that attempts to develop machines that are capable of emulating human thought processes. Expert systems were a result of the understanding gained by AI researchers about the role played by knowledge in the cognitive process [2]. An expert dealing with a problem in a certain field often uses very simple reasoning, relying more upon knowledge gained from years of experience. The realization of this fact encouraged researchers to build systems that apply simple reasoning mechanisms to knowledge about a very specific area of expertise. These systems were called "expert systems", and a new field began.

Definition

The term "expert system" refers to a system that uses contemporary computer technology to store and interpret the knowledge and experience of a human expert in a specific area of interest [3]. By accessing this computer-based knowledge, a non-expert can get the benefit of expert advice in that area.

A more formal definition of an expert system is that it is an interactive computer-based decision tool that uses both facts and heuristics to solve difficult decision problems, based on knowledge acquired from a human expert [4].

Characteristics

The most obvious feature of an expert system is its interactive user interface. An expert system acts as an interactive system that responds to questions, asks for clarifications and provides suggestions. Behind this interface lie other characteristics that may not be immediately apparent to the user, some of which are listed below [3]:

- An expert system has the ability to store and sift through significant amounts of knowledge.
- It also supports mechanisms to expand and improve the knowledge base on a continuing basis, in order to keep the system up-to-date.
- It has the capability to make logical inferences based on the knowledge stored.
- A particular expert system caters to a relatively narrow area of specialization.

The focus on a narrow area of specialization is a result of technological limitations. As the scope of an expert system is widened, its knowledge base needs to be expanded. The methodologies available today limit the amount of knowledge

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that can be stored and retrieved in reasonable amounts of time. So, the constraints set by existing technology make it necessary for expert systems to cater to relatively narrow domains.

Anatomy

An expert system has three levels of organization — a *knowledge base*, a *working memory* and an *inference engine* [4]. Apart from these, it has a user interface which permits the user to interact with the system.

Knowledge Base. The knowledge base contains the formal representation of the information provided by the domain expert. This information may be in the form of problem-solving rules, procedures, or data intrinsic to the domain.

In order to convert the knowledge acquired from the human expert into a form suitable for manipulation by a computer, it is necessary to make use of one or more knowledge representation methods. A detailed description of some these methods can be found in [4] and [5].

Working Memory. This term refers to the task-specific data for a problem. This may consist of the set of conditions leading up to the problem, the parameters describing the problem, and so on. This is the only part of the expert system that is subject to rapid change. As the problem data needs to be supplied to the system by the user, the user interface is closely related to the working memory.

Inference Engine. The inference engine is the generic control mechanism that applies the axiomatic knowledge present in the knowledge base to the task-specific data to arrive at some conclusion. The knowledge base and the inference engine together form the core of the expert system.

An inference engine essentially navigates through the knowledge base, searching for pieces of information relevant to the problem at hand. It then uses some reasoning mechanism to make certain inferences by applying the relevant information to the problem data.

As expert systems usually have very large knowledge bases, it is necessary for inference engines to use certain search strategies and reasoning mechanisms in order to improve their efficiency. Details on common search strategies such as depth-first and breadth-first searches, and reasoning mechanisms like forward and backward chaining can be found in [4] and [5].

User Interface. An ideal expert system should have a user interface designed to operate at a level similar to ordinary conversation. Some of the typical characteristics of the user interface are:

- It allows the user to input data relevant to the problem at any stage of the consultation process.
- It allows the user to ask the expert system how it reached a certain conclusion, or why it is following a certain line of reasoning.
- It allows the user to examine the knowledge base.
- It not only provides the user with solutions and recommendations, but also gives the user a level of confidence about the solution.

An expert system is not guaranteed to come up with an exact or optimal solution all the time. The quality of the solution depends on the quality of the available problem data. The confidence level provided by the expert system is a measure of the quality of the solution, and therefore, is a measure of the quality of the information available about the problem.

Justification

Before designing an expert system for any problem, it must be demonstrated that the problem is suitable for an expert systems approach, and that the expert system to be designed will be feasible and reliable. Therefore, it is necessary to show that the problem of estimating the electromagnetic radiation from printed circuit boards and identifying potential EMC problems is suitable for an expert systems application, and that such an expert system would be practical.

As an expert system is based on symbolic reasoning, one of the main criteria for problem selection is that the problem must lend itself to symbolic representation and processing. The analysis of a board layout requires the manipulation and processing of component and net structures, and an understanding of the relation between components and nets. Nets and components lend can readily be represented as symbols to be processed by the expert system.

If finding a solution to a problem requires a lot of "common sense" reasoning, then the problem is not suited to be an expert system application. This is because there is no easy way to incorporate the enormous quantity of common sense knowledge into the knowledge base of an expert system.

The methods used by a human EMC expert to estimate the radiated energy from a board, or to identify potential EMC problems, are based on Maxwell's laws of electromagnetism and a knowledge of the voltages and currents on the board. These methods usually do not involve "common sense" reasoning in the broad sense of the term.

Problems requiring exact solutions should not be selected as expert systems applications, because an expert system is not designed to produce an exact solution. The problem of predicting radiated emissions satisfies this criterion for problem selection, as there is really no exact or optimal solution possible for the problem. The results of an actual EMI test vary from one test site to another. So, any prediction that comes within a few dB of the results of an actual EMI test can be considered to be accurate enough for practical purposes.

One of the criteria for deciding the feasibility of an expert system is determining if maintenance of the knowledge base is expected to present difficulties. As is explained later in this paper, the one part of the knowledge base of the EMC expert system that needs regular maintenance and updating is the *component library*, which contains information on components that is not available from the board layout files. This component information is either easily available from vendor-supplied component data, or can be entered by the EMC expert responsible for maintaining the component library, based on experience.

There must be a sufficient number of test cases available in order to evaluate the performance of the system. Since any product that has undergone an EMI test becomes a test case for the EMC expert system, this criterion is easily satisfied.

It must be determined if the intended end-user of the expert system would be willing to use such a system. The end-user of the EMC expert system is envisaged to be any person involved in the design of an electronic device that needs to be tested for EMC compliance. As the expert system is designed to be easy to use and does not require the user to be an expert in EMC or circuit design, while providing the same results as conventional numerical or analytical modeling tools, it should become the preferred EMC analysis tool of the non-expert.

The EMC Expert System

Figure 1 shows the basic structure of the EMC expert system. The expert system consists of four stages — the input stage, the evaluation stage, the estimation stage and the output stage. Each stage is made up of several modules, with each module performing a certain task. This modular structure makes it easy for a person to understand and modify the functional capability of the system.

The Input Stage

Information about the printed circuit board under analysis is collected by the input stage of the expert system. Physical information about the board, such as board geometry, names and locations of all nets and components, trace lengths and thicknesses etc., is obtained from board layout files generated by automated layout tools. The electrical properties of each net, such as signal frequencies, currents, voltages etc., are deduced by collating information from the layout files and the *component library*.

The component library is a file that contains information about components that is not present in the board layout files. It is meant to be a central database of information about all components that the system may encounter when analyzing PCB's for a particular set of users. The component library for an expert system being used by one set of users may be different from that for an expert system being used by a different set of users.

The component library contains component information at two levels — the package level and the pin level. Package level information about a component includes the component name, package size and type, pin pitch etc. Pin-level information about a component is provided for each pin of the component, and is dependent on whether the device is active, series passive (e.g., resistors, capacitors etc.), N-port passive (e.g., transformers, common-mode chokes etc.), or a connector.

For active devices only, the pin-level information provided is different for input pins, output pins and power/ground pins within the component. For example, each input pin of an active device would have an entry in the component library that specifies the input impedance at the pin, the typical signal frequencies entering the device through the pin etc. Information about each output pin of an active device includes the maximum and minimum voltage output, maximum current output etc. A more detailed description of the component library as well as the other parts of the EMC expert system can be found in [6].

As the component library is a part of the knowledge base of the expert system, the maintenance of this database is the responsibility of EMC experts. While most of the information requested by the component library is readily available from vendor-supplied data, certain pieces of information may have to be entered by an EMC expert, based on experience. The expert system does not require the information provided in the component library to be complete, but the quality of its results depends on the completeness and accuracy of the information provided.

The *EMC personality file* is another part of the knowledge base for the expert system. This file contains industry-specific EMC guidelines within which the expert system must work. This information is necessary because different industries have different design requirements and different EMC design strategies [7]. The information contained in this file helps the expert system to prioritize its rules and evaluation strategies.

The data from the layout files and the component library is used by the *net classification algorithm* to determine information about the signal properties, noise margin and function of each net on the board. It also searches for possible layout problems, such as nets being referenced to more than one power source, or nets being driven by more than one driver, and alerts the user about such problems.

The algorithm identifies all power and ground nets on the board by checking each net to see if any of the pins attached to it are specified to be power or ground in the component library. Nets that are neither power nor ground are called "signal" nets.

Each net is classified as "I/O" or "non-I/O" depending on whether a connector pin is attached to the net or not. Each net is also classified as "analog" or "digital" based on whether the active device pins on the net are specified to be analog or digital in the component library. Nets having both types of pins are identified as possible layout problems.

Each net is assigned a *radiation classification* of R1, R2 or R3, which is a measure of the radiation potential of the signal on the net. A classification of R3 implies that the signal on the net is capable of causing serious radiation problems, while a classification of R1 implies a low radiation potential. These net classifications are based on similar classifications assigned to pins in the component library.

A *susceptibility classification* of S1, S2 or S3 is also assigned to each net, which provides a measure of the ease with which the signal on the net can be corrupted by external noise. An S3 net is most susceptible to interference, while an S1 net is most immune to noise. These classifications are also based on similar classifications assigned to pins in the component library.

The classification algorithm determines various signal parameters for each "signal" net. These parameters are determined from the component library entry for the driver for the net. The algorithm locates a driver by checking to see if any active device output pin is connected to the net either directly or through passive devices.

The signal parameters determined by the classification algorithm consist of the clock frequency associated with each digital net, the range of signal frequencies on each analog net, the signal transition time for each digital net, the maximum and minimum voltages on each net, the maximum current on each

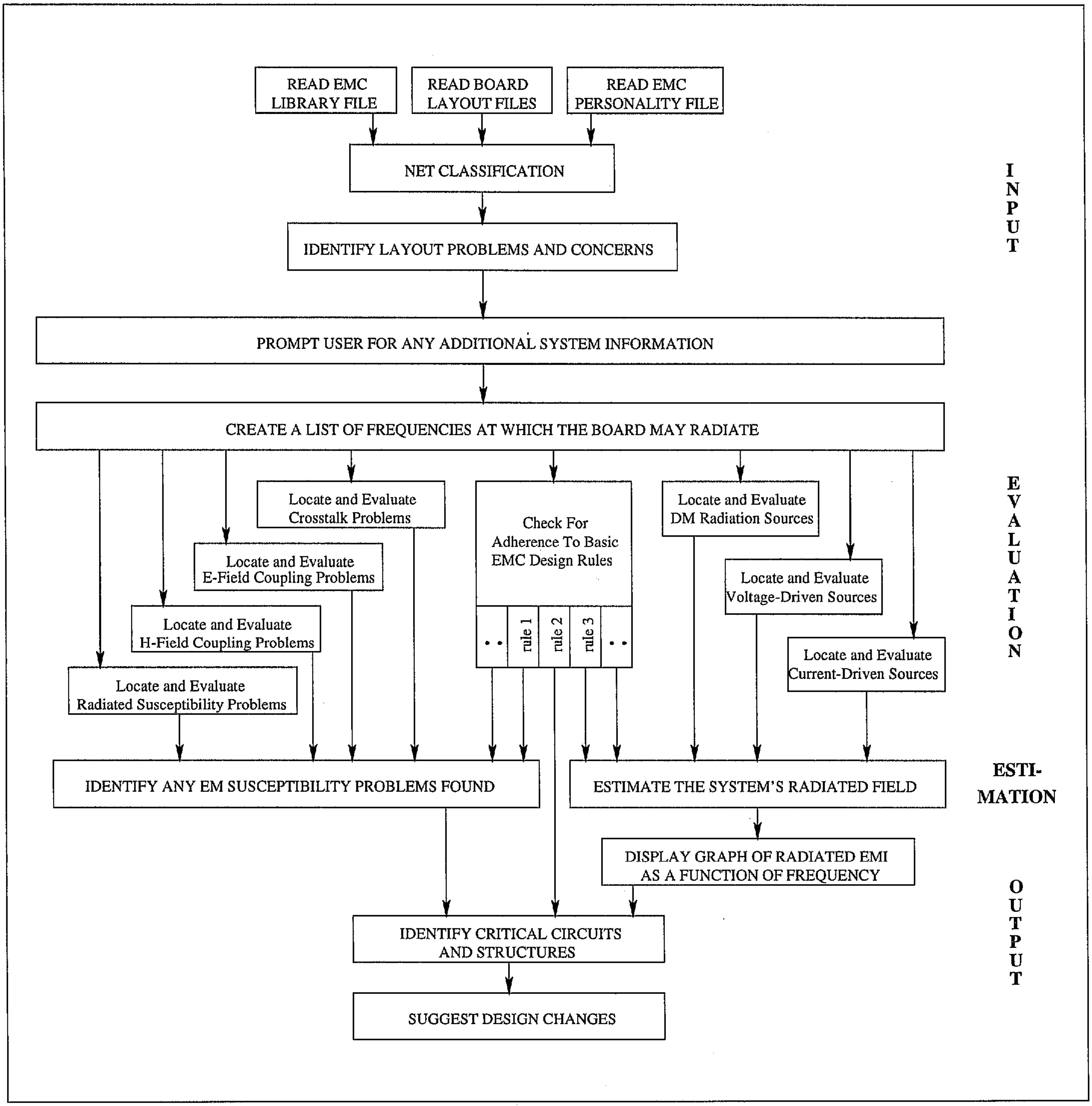

Figure 1: The Basic Structure of the EMC Expert System

net, the reference voltage for each net, and the *utilization* classification of each net. Each net is assigned a utilization of HIGH, MEDIUM or LOW, which is a measure of the percentage of time the signal on the net is "active".

Each "signal" net is also assigned a *noise margin*, which is the maximum voltage that may exist on the net without interfering with the normal behavior of the components on the net. This assignment is based on the noise margins of the active device input pins on the net, as specified in the component library.

The algorithm identifies the return path of the signal on each segment of each "signal" net on the board. While driver information plays a role in the identification, in most cases, the return path is determined to be the power or ground plane closest to the segment under consideration.

After the classification algorithm finishes its run, its results are made available to the user, who is given a chance to modify the results, or provide information that may fill in any gaps in the available information. If the user is satisfied with these results, they are passed to the evaluation stage of the EMC expert system.

The Evaluation Stage

The evaluation stage of the expert system contains the modules that perform a detailed EMC analysis of the board. These modules search for potential radiation and susceptibility problems with the board, and also test the board for compliance with basic EMC design guidelines.

The expert system creates a list of all the clock frequencies on the board, and their harmonics, and all narrow-band analog signal frequencies. The narrow-band radiation from the board is calculated at these frequencies only. The frequency spectrum is also divided into blocks at which the broadband radiation is calculated. These blocks are created in such a way that each block is centered at a narrow-band frequency, and fills the space between narrow-band frequencies.

The EMC expert system is capable of identifying and evaluating three radiated EMI source mechanisms — the differential-mode radiation mechanism, the common-mode "voltage-driven" mechanism, and the common-mode "current-driven" mechanism.

Differential-mode radiation refers to the electric field radiation from a current loop. The current on each segment on the board has a return path identified earlier by the classification algorithm. The segment and the return path form a complete current loop.

The expert system calculates the E-fields at each narrow-band frequency, due to the current loops formed by segments on HIGH utilization nets and their return paths. MEDIUM utilization nets are used to calculate the broadband radiation at each frequency block.

The common-mode "voltage-driven" mechanism consists of a voltage source on the board driving an antenna, which may be a heatsink, an enclosure, or a cable. The voltage source generates a common-mode current on the antenna, which is responsible for the radiation. The current on the antenna may be an intentional signal, such as a signal being carried out of the board to a peripheral device on a cable, or it may be due to an unintentional signal coupling onto the antenna, e.g., coupling from a high-speed clock line to a cable.

The expert system locates potential antennas and the voltage sources that may be intentionally or unintentionally driving those antennas. For example, it calculates the noise voltage induced on each I/O net, due to the coupling of signals from nearby nets with radiation classifications of R2 or R3. The noise voltage induced on an I/O net drives the cable attached to the net through the connector. The E-field radiation from all such voltage-driven mechanisms is estimated at each frequency and frequency block.

At high frequencies, there is a significant variation in voltage across the return (ground/power) plane structure of a PCB. Currents returning on the plane create potential drops across the partial inductance of the plane. These variations in potential drive various antenna structures, thus generating a significant amount of radiated EMI. This comprises the common-mode "current-driven" mechanism.

The expert system estimates the two-dimensional voltage variation across the return plane structure, due to currents returning on the power and ground planes. It then locates the antennas that may be driven by this voltage variation. The expert system is capable of identifying antenna configurations such as a cable being driven relative to another cable or a heatsink, a cable or heatsink being driven relative to the board etc. For each such antenna, it determines the voltage difference between the two halves of the antenna, and then calculates the E-field radiated from the antenna at each frequency and frequency block.

Algorithms are also included that identify crosstalk problems, estimate power bus noise, and check the design for violations of basic EMC design guidelines.

While the EMC component library and the personality file form the knowledge base, the net classification algorithm and the entire evaluation stage are the inference engines of the EMC expert system. These inference engines apply a built-in set of rules to the information available from the knowledge base to deduce additional information about the board under analysis.

The Estimation and Output Stages

The results from all the modules in the evaluation stage are passed to the estimation stage, which combines these results to form an overall estimate of the radiated EMI from the board.

The radiated EMI modules in the evaluation stage calculate the magnitudes of the electric fields due to each of the radiated EMI mechanisms, at each frequency and frequency block.

The output stage presents the expert system's evaluation of the board to the user. It displays a graph of the estimated radiated EMI as a function of frequency, and identifies the circuits and structures on the board that are mainly responsible for the board's radiated EMI problems. It also suggests design changes that will alleviate the problems reported.

The radiated EMI plot displayed by the expert system is similar to that which would be obtained from an actual EMI test. It plots the board's radiated field in dB(μV/m) against frequency. An FCC or CISPR limit line is placed on the plot, so as to give the user an immediate idea of the frequencies at which the board radiation exceeds the limit, and the amount (in dB) of excess radiation at those frequencies.

Significant contributions of individual nets to the radiated E-field are recorded at each frequency and frequency block by the modules of the evaluation stage. These are used to construct a list of nets causing the worst problems at any particular frequency or block. So, if the user would like to know which nets are causing the radiation to exceed the limit at any frequency, the expert system can list all such nets and display a diagram of the board layout that highlights these nets. Information about the mechanisms that cause these violations is also available to the user.

The expert system also offers suggestions that will help in reducing radiated EMI levels. As the chief contributors to the emissions are known to the system, it uses some simple rules to come up with viable suggestions that will reduce the contributions from the worst offenders.

As the estimation stage is just an extension of the evaluation stage, it is also a part of the inference engine of the expert system. The output stage is a part of the interactive user interface, in which the user can regulate the amount of information provided by the expert system.

Conclusion

While there are a number of EMC analysis software tools available on the market, few engineers possess the knowledge and experience required to use these tools effectively. Expert systems provide a solution to this problem, as they are capable of producing the same kind of results as existing software, while not requiring the user to be an EMC expert.

The EMC expert system described in this paper models the thinking process of a human EMC expert. It reads in board layout information from the files produced by automated board layout tools. It then uses the information stored in its knowledge base (the component library) to deduce certain signal properties and the function of each net on the board. This information is used to identify and evaluate possible radiation sources and antennas, and provide an overall estimate of board radiation. It also provides suggestions that help in reducing radiated EMI levels.

The quality of the information provided in the component library determines the accuracy of the expert system's estimate. Therefore, it is important to update the component library on a regular basis. The component library needs to be maintained by experts, while the expert system itself can be used by anyone.

The EMC expert system is not designed to replace the human EMC expert. It simply takes care of some of the more mundane tasks performed by the human expert. The idea behind this is that when the board is finally brought before a human expert, the board is largely clean, and the expert can concentrate on the more subtle problems with the board.

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