

A Survey of Online Failure Prediction Methods

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With ever-growing complexity and dynamicity of computer systems, proactive fault management is an effective approach to enhancing availability. Online failure prediction is the key to such techniques. In contrast to classical reliability methods, online failure prediction is based on runtime monitoring and a variety of models and methods that use the current state of a system and, frequently, the past experience as well. This survey describes these methods. To capture the wide spectrum of approaches concerning this area, a taxonomy has been developed, whose different approaches are explained and major concepts are described in detail.

Categories and Subject Descriptors: C.4 [Performance of Systems]: Reliability, availability, and serviceability; Fault tolerance; D.2.5 [Testing and Debugging]: Error handling and recovery

General Terms: Algorithms, Reliability

Additional Key Words and Phrases: Error, failure prediction, fault, prediction metrics, runtime monitoring

1. INTRODUCTION

Predicting the future has fascinated people from the beginning of times. Several millions of people work on prediction daily: astrologers, meteorologists, politicians, pollsters, stock analysts and doctors as well as computer scientists and engineers. As computer scientists we focus on the prediction of computer system failures, a topic that has attracted interest for more than 30 years. However, what is understood by the term “failure prediction” varies among research communities and has also changed over the decades.

As computer systems are growing more and more complex, they are also changing dynamically due to the mobility of devices, changing execution environments, frequent updates and upgrades, online repairs, the addition and removal of system components and the systems/networks complexity itself. Classical reliability theory and conventional methods do rarely consider the actual state of a system and are therefore not capable to reflect the dynamics of runtime systems and failure processes. Such methods are typically useful in design for long term or average behavior predictions and comparative analysis.

The motto of research on online failure prediction techniques can be well expressed by the words of the Greek poet C. P. Cavafy, who said [Cavafy 1992]:

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“Ordinary mortals know what’s happening now, the gods know what the future holds because they alone are totally enlightened. Wise men are aware of future things just about to happen.”

For ordinary mortals, predicting the near term future is more clever and frequently more successful than attempting long term predictions. Short term predictions are especially helpful to prevent potential disasters or to limit the damage caused by computer system failures. Allowing for the dynamic properties of modern computer systems online failure prediction incorporates measurements of actual system parameters during runtime in order to assess the probability of failure occurrence in the near future in terms of seconds or minutes.

1.1 Focus of this Survey

In computer science, prediction methods are used in various areas. For example, branch prediction in microprocessors tries to prefetch instructions that are most likely to be executed, or memory or cache prediction tries to forecast what data might be required next. Limiting the scope to failures, there are several areas where the term prediction is used. For example, in reliability theory, the goal of reliability prediction the goal is to assess future reliability of a system from its design or specification. The book [Lyu 1996], and especially the chapters [Farr 1996] and [Brocklehurst and Littlewood 1996], provide a good overview, while the books [Musa et al. 1987; Blischke and Murthy 2000] cover the topic comprehensively. Denson [1998] gives an overview of reliability prediction techniques for electronic devices. However,

the topic of this survey is to identify *during runtime* whether a failure will occur in the *near future* based on an assessment of the *monitored current system state*. Such type of failure prediction is called *online failure prediction*.

Although architectural properties such as interdependencies play a crucial role in some prediction methods, online failure prediction is concerned with a *short-term* assessment that allows to decide, whether there will be a failure, e.g., five minutes ahead or not. Prediction of systems reliability, however, is concerned with long-term predictions based on, e.g., failure rates, architectural properties, or the number of bugs that have been fixed.

Online failure prediction is frequently confused with *root cause analysis*. Having observed some misbehavior in a running system, *root cause analysis* tries to identify the fault that caused it, while *failure prediction* tries to assess the risk that the misbehavior will result in future failure (see Figure 1). For example, if it is observed

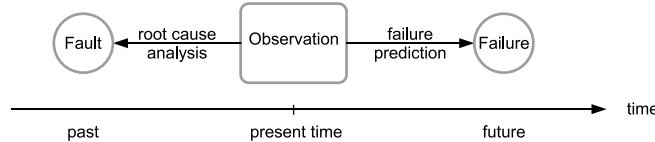


Fig. 1. Distinction between root cause analysis and failure prediction.

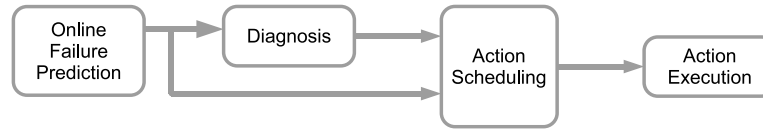


Fig. 2. The steps involved in proactive fault management. After prediction of an upcoming failure, diagnosis might be required in order to find the fault that causes the upcoming failure. Failure prediction and/or diagnosis results are used to decide upon which proactive method to apply and to schedule their execution.

that a database is not available, root cause analysis tries to identify what the reason for unavailability is: a broken network connection, or a changed configuration, etc. Failure prediction on the other hand tries to assess whether this situation bears the risk that the system cannot deliver its expected service, which may depend on system characteristics, failure prediction model and the current situation: is there a backup database or some other fault tolerance mechanism available? What is the current load of the system? This survey focuses on failure prediction only.

1.2 The Big Picture: Proactive Fault Management

When both industry and academia realized that traditional fault tolerance mechanisms could not keep pace with the growing complexity, dynamics and flexibility of new computing architectures and paradigms, they set off the search for new concepts as can be seen from initiatives and research efforts on autonomic computing [Horn 2001], trustworthy computing [Mundie et al. 2002], adaptive enterprise [Coleman and Thompson 2005], recovery-oriented computing [Brown and Patterson 2001], and various conferences on self-*properties where the asterisk can be replaced by any of “configuration”, “healing”, “optimization”, or “protection” (see, e.g., [Babaoglu et al. 2005]). Most of these terms span a variety of research areas ranging from adaptive storage to advanced security concepts. One of these areas is concerned with the task how computer systems can proactively handle failures: if the system knows about a critical situation in advance, it can try to apply countermeasures in order to prevent the occurrence of a failure, or it can prepare repair mechanisms for the upcoming failure in order to reduce time-to-repair. In analogy to the term “fault tolerance”, we use *proactive fault management* as an umbrella term for these techniques.

Proactive fault management consists basically of four steps (see Figure 2):

- (1) In order to identify failure-prone situations, i.e. situations that will probably evolve into a failure, *online failure prediction* has to be performed. The output of online failure prediction can either be a binary decision or some continuous measure judging the current situation as more or less failure-prone.
- (2) Even though techniques such as checkpointing can be triggered directly by a binary failure prediction algorithm, further *diagnosis* is required in many other cases. The objective is, dependent on the countermeasures that are available in the system, to find out where the error is located (e.g., at which component) or what the underlying fault is. Note that in contrast to traditional diagnosis, in proactive fault management diagnosis is invoked by failure prediction, i.e.,

when the failure is imminent but has not yet occurred.

- (3) Based on both the outcome of online failure prediction and/or diagnosis, a decision needs to be made which of the actions, i.e., countermeasures, should be applied and when it should be executed in order to remedy the problem. This step is termed *action scheduling*. These decisions are based on an objective function taking cost of actions, confidence in the prediction, effectiveness and complexity of actions into account in order to determine the optimal trade-off. For example, in order to trigger a rather costly technique the scheduler should be almost sure about an upcoming failure, whereas for a less expensive action less confidence in the correctness of failure prediction is required. Candea et al. [2004] have examined this relationship quantitatively. They showed that short restart times (microreboots) allow for a higher false positive rate in comparison to slower restarts (process restarts).¹ Many emerging concepts such as the policies used in IBM's autonomic manager relate to action scheduling, as well.
- (4) The last step in proactive fault management is the actual *execution of actions*. Challenges for action execution include online reconfiguration of globally distributed systems, data synchronization of distributed data centers, and many more.

In summary, accurate online failure prediction is only the prerequisite in the chain and each of the remaining three steps constitutes a whole field of research on its own. Not devaluing the efforts that have been made in the other fields, this survey provides an overview of online failure prediction.

In order to build a proactive fault management solution that is able to boost system dependability by up to an order of magnitude, the best techniques from all four fields for the given surrounding conditions have to be combined. However, this requires *comparability* of approaches which can only be achieved if two conditions are met:

- a set of standard quality evaluation metrics is available
- publicly available reference data sets can be accessed.

Regarding reference data sets, a first initiative has been started in 2006 by Carnegie Mellon University called the Computer Failure Data Repository (<http://cfdm.usenix.org>) that publicly provides detailed failure data from a variety of large production systems such as high performance clusters at the Lawrence Livermore National Laboratory.

Regarding standard metrics, this survey provides the first step by presenting and discussing major metrics for the evaluation of online failure prediction approaches.

1.3 Outline

This article is a survey on failure prediction methods that have been used to predict failures of computer systems online, i.e., based on the current system state. Starting from a definition of the basic terms such as errors, failures and lead time

¹Although in the paper by Candea et al. [2004] false positives relate to falsely suspecting a component to be at fault, similar relationships should hold for failure predictions, too.

(Section 2), established metrics to investigate the quality of failure prediction algorithms are reviewed in Section 3. In order to structure the wide spectrum of methods, a taxonomy is introduced in Section 4 and almost fifty online failure prediction approaches are surveyed in Section 5. A comprehensive list of all failure prediction methods together with demonstrated and potential applications is provided in the summary and conclusions (Section 6). In order to give further insight into online failure prediction approaches, selected representative methods are described in greater detail in the appendix: In Appendix A a table of the selected methods is provided and the techniques are discussed in Appendices B-K.

2. DEFINITIONS

The aim of online failure prediction is to predict the occurrence of failures during runtime based on the current system state. The following sections provide more precise definitions of the terms used throughout this article.

2.1 Faults, Errors, Symptoms, and Failures

Several attempts have been made to get to a precise definition of faults, errors, and failures, among which are [Melliar-Smith and Randell 1977; Avižienis and Laprie 1986; Laprie and Kanoun 1996; IEC: International Technical Commission 2002], [Siewiorek and Swarz 1998, Page 22], and most recently [Avižienis et al. 2004]. Since the latter seems to have broad acceptance, its definitions are used in this article with some additional extensions and interpretations.

- A *failure* is defined as “an event that occurs when the delivered service deviates from correct service”. The main point here is that a failure refers to misbehavior that can be observed by the user, which can either be a human or another computer system. Things may go wrong inside the system, but as long as it does not result in incorrect output (including the case that there is no output at all) there is no failure.
- The situation when “things go wrong” in the system can be formalized as the situation when the system’s state deviates from the correct state, which is called an *error*. Hence, “an error is the part of the total state of the system that may lead to its subsequent service failure.”
- Finally, *faults* are the adjudged or hypothesized cause of an error – the root cause of an error. In most cases, faults remain dormant for some time and once they become active, they cause an incorrect system state, which is an error. That is why errors are also called “manifestation” of faults. Several classifications of faults have been proposed in the literature among which the distinction between transient, intermittent and permanent faults [Siewiorek and Swarz 1998, Page 22] is best known.
- The definition of an error implies that the activation of a fault lead to an incorrect state, however, this does not necessarily mean that the system knows about it. In addition to the definitions given by [Avižienis et al. 2004], we distinguish between *undetected errors* and *detected errors*: An error remains undetected until an error detector identifies the incorrect state.
- Besides causing a failure, undetected or detected errors may cause out-of-norm behavior of system parameters as a side-effect. We call this out-of-norm be-

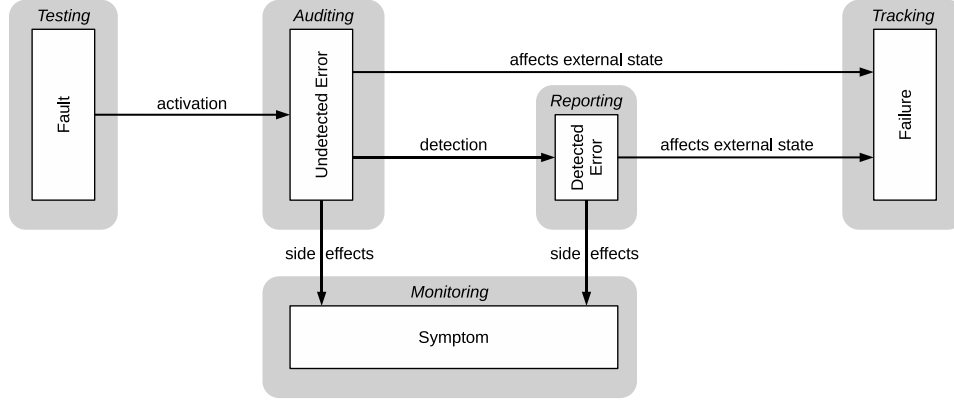


Fig. 3. Interrelations of faults, errors, symptoms, and failures. Encapsulating boxes show the technique by which the corresponding flaw can be made visible.

havior a *symptom*.² In the context of *software aging*, symptoms are similar to *aging-related errors*, as implicitly introduced in [Grottke and Trivedi 2007] and explicitly named in [Grottke et al. 2008].

Figure 3 visualizes how a fault can evolve into a failure. Note that there can be an m-to-n mapping between faults, errors, symptoms, and failures: For example, several faults may result in one single error or one fault may result in several errors. The same holds for errors and failures: Some errors result in a failure some errors do not, and more complicated, some errors only result in a failure under special conditions. As is also indicated in the figure, an undetected error may cause a failure directly or might even be non-distinguishable from it. Furthermore, errors do not necessarily show symptoms.

To further clarify the terms fault, error, symptom, and failure, consider a fault-tolerant system with a memory leak in its software. The fault is, e.g., a missing **free** statement in the source code. However, as long as this part of the software is never executed, the fault remains dormant. Once the piece of code that should free memory is executed, the software enters an incorrect state, i.e., it turns into an error (memory is consumed and never freed although it is not needed anymore). If the amount of unnecessarily allocated memory is sufficiently small, this incorrect state will neither be detected nor will it prevent the system from delivering its intended service (no failure is observable from the outside). Nevertheless, if the piece of code with the memory leak is executed many times, the amount of free memory will slowly decrease in the long run. This out-of-norm behavior of the system parameter “free memory” is a symptom of the error. At some point in time, there might not be enough memory for some memory allocation and the error is detected. However, if it is a fault-tolerant system, the failed memory allocation still does not necessarily lead to a service failure. For example, the operation might be completed by some spare unit. Only if the entire system, as observed from the

²This should not be confused with Iyer et al. [1986], who use the term *symptom* for the most significant errors within an error group

outside, cannot deliver its service correctly, a failure occurs.

2.2 Online Prediction

The task of online prediction is visualized in Figure 4: At present time t , the

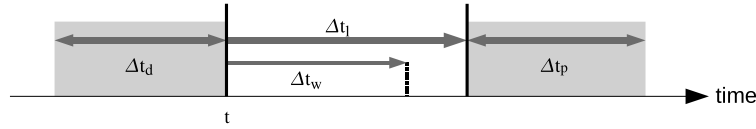


Fig. 4. Time relations in online failure prediction. Present time is denoted by t . Failures are predicted with lead-time Δt_l , which must be greater than minimal warning-time Δt_w . A prediction is assumed to be valid for some time period, named prediction-period, Δt_p . In order to perform the prediction, some data up to a time horizon of Δt_d are used. Δt_d is called data window size.

potential occurrence of a failure is to be predicted some time ahead (lead-time Δt_l) based on the current system state, which is assessed by system monitoring within a data window of length Δt_d . The prediction is valid for some time interval Δt_p , which is called the prediction period. Increasing Δt_p increases the probability that a failure is predicted correctly.³ On the other hand, if Δt_p is too large, the prediction is of little use since it is not clear when exactly the failure will occur. Since failure prediction does not make sense if the lead-time is larger than the time the system needs to react in order to avoid a failure or to prepare for it, Figure 4 introduces the minimal warning time Δt_w . If lead-time were shorter than the warning time, there would not be enough time to perform any preparatory or preventive actions.

3. EVALUATION METRICS

In order to investigate the quality of failure prediction algorithms and to compare their potential it is necessary to specify metrics (figures of merit). It is the goal of failure prediction to predict failures accurately: covering as many failures as possible while at the same time generating as few false alarms as possible. A perfect failure prediction would achieve a one-to-one matching between predicted and true failures. This section will introduce several established metrics for the goodness of fit of prediction. Some other metrics have been proposed, e.g., the kappa statistic [Altman 1991, Page 404], but they are rarely used by the community. A more detailed discussion and analysis of evaluation metrics for online failure prediction can be found in [Salfner 2008, Chapter 8.2].

Table I defines four cases: A failure prediction is a true positive if a failure occurs within the prediction period and a failure warning is raised. If no failure occurs and a warning is given, the prediction is a false positive. If the algorithm misses to predict a true failure, it is a false negative. If no true failure occurs and no failure warning is raised, the prediction is a true negative.

³For $\Delta t_p \rightarrow \infty$, simply predicting that a failure will occur would always be 100% correct!

Table I. Contingency table. Any failure prediction belongs to one out of four cases: if the prediction algorithm decides in favor of an upcoming failure, which is called a *positive*, it results in raising a failure warning. This decision can be right or wrong. If in reality a failure is imminent, the prediction is a true positive. If not, a false positive. Analogously, in case the prediction decides that the system is running well (a negative prediction) this prediction may be right (true negative) or wrong (false negative)

	True Failure	True Non-failure	Sum
Prediction: Failure (failure warning)	true positive (<i>TP</i>) (correct warning)	false positive (<i>FP</i>) (false warning)	positives (<i>POS</i>)
Prediction: No failure (no failure warning)	false negative (<i>FN</i>) (missing warning)	true negative (<i>TN</i>) (correctly no warning)	negatives (<i>NEG</i>)
Sum	failures (<i>F</i>)	non-failures (<i>NF</i>)	total (<i>N</i>)

3.1 Contingency Table Metrics

The metrics presented here are based on the contingency table (see Table I) and therefore called “contingency table metrics”. They are often used in pairs such as precision/recall, true positive rate/false positive rate, sensitivity/specificity and positive predictive value/negative predictive value. Table II provides an overview.

In various research areas, different names have been established for the same metrics. Hence the leftmost column indicates which terms are used in this paper, and the rightmost column lists additional names.

Precision is defined as the ratio of correctly identified failures to the number of all predicted failures.

$$precision = \frac{TP}{TP + FP} \quad (1)$$

Recall is the ratio of correctly predicted failures to the number of true failures.

$$recall = \frac{TP}{TP + FN} \quad (2)$$

Consider the following example for clarification: A prediction algorithm that achieves precision of 0.8, generates correct failure warnings (referring to true failures) with a probability of 0.8 and false positives with a probability of 0.2. A recall of 0.9 expresses that 90% of all true failures are predicted and 10% are missed.

In [Weiss 1999], variants of precision and recall have been introduced that accounts for multiple predictions of the same failure and of bursts of false positive predictions.

Improving precision, i.e., reducing the number of false positives, often results in worse recall, i.e., increasing the number of false negatives, at the same time. To integrate the trade-off between precision and recall the F-Measure was introduced by van Rijsbergen [1979, Chapter 7] as the harmonic mean of precision and recall. Assuming equal weighting of precision and recall, the resulting formula is

$$F\text{-measure} = \frac{2 \cdot precision \cdot recall}{precision + recall} \in [0, 1] \quad (3)$$

The higher the quality of the predictor, the higher the F-measure. If precision and recall both approach zero, the limit of the F-measure is also zero.

Table II. Metrics obtained from contingency table (c.f., Table I). Different names for the same metrics have been used in various research areas, as listed in the rightmost column.

Name of the metric	Formula	Other names
Precision	$\frac{TP}{TP+FP} = \frac{TP}{POS}$	Confidence Positive predictive value
Recall True positive rate	$\frac{TP}{TP+FN} = \frac{TP}{F}$	Support Sensitivity Statistical power
False positive rate	$\frac{FP}{FP+TN} = \frac{FP}{NF}$	Fall-out
Specificity	$\frac{TN}{TN+FP} = \frac{TN}{NF}$	True negative rate
False negative rate	$\frac{FN}{TP+FN} = \frac{FN}{F}$	1 - recall
Negative predictive value	$\frac{TN}{TN+FN} = \frac{TN}{NEG}$	
False positive error rate	$\frac{FP}{FP+TP} = \frac{FP}{POS}$	1 - precision
Accuracy	$\frac{TP+TN}{TP+TN+FP+FN} = \frac{TP+TN}{N}$	
Odds ratio	$\frac{TP \cdot TN}{FP \cdot FN}$	

One problem with precision and recall is that they do not account for true negative predictions. Hence the following metrics should be used in combination with precision and recall. The false positive rate is defined as the ratio of incorrectly predicted failures to the number of all non-failures. The smaller the false positive rate, the better, provided that the other metrics are not changed for the worse.

$$\text{false positive rate} = \frac{FP}{FP + TN} \quad (4)$$

Specificity is defined as the ratio of all correctly not raised failure warnings to the number of all non-failures.

$$\text{specificity} = \frac{TN}{FP + TN} = 1 - \text{false positive rate} \quad (5)$$

The negative predictive value (NPV) is the ratio of all correctly not raised failure warnings to the number of all not raised warnings.

$$\text{negative predictive value} = \frac{TN}{TN + FN} \quad (6)$$

Accuracy is defined as the ratio of all correct predictions to the number of all predictions that have been performed.

$$\text{accuracy} = \frac{TP + TN}{TP + FP + FN + TN} \quad (7)$$

Due to the fact that failures usually are rare events, accuracy does not appear to be an appropriate metric for failure prediction: a strategy that always classifies the system to be non-faulty can achieve excellent accuracy since it is right in most of the cases, although it does not catch any failure (recall is zero).

From this discussion it might be concluded that true negatives are not of interest for the assessment of failure prediction techniques. This is not necessarily true since the number of true negatives can help to assess the impact of a failure prediction approach on the system. Consider the following example: For a given time period including a given number of failures, two prediction methods do equally well in terms of TP , FP , and FN , hence both achieve the same precision and recall. However, one prediction algorithm performs ten times as many predictions as the second since, e.g., one operates on measurements taken every second and the other on measurements that are taken only every ten seconds. The difference between the two methods is reflected only in the number of TN and will hence only become visible in metrics that include TN . The number of true negatives can be determined by counting all predictions that were performed when no true failure was imminent and no failure warning was issued as a result of the prediction.

It should also be pointed out, that quality of predictions depends not only on algorithms but also on the data window size Δt_d , lead-time Δt_l , and prediction-period Δt_p . For example, since it is very unlikely to predict that a failure will occur at one exact point in time but only within a certain time interval (prediction period), the number of true positives depends on Δt_p : the longer the prediction period, the more failures are captured and hence the number of true positives goes up, which affects, e.g., recall. That is why the contingency table should only be determined for one specific combination of Δt_d , Δt_p and Δt_l .

3.2 Precision/Recall-Curve

Many failure predictors involve an adjustable decision threshold, upon which a failure warning is raised or not. If the threshold is low, a failure warning is raised very easily which increases the chance to catch a true failure (resulting in high recall). However, a low threshold also results in many false alarms which leads to low precision. If the threshold is very high, the situation is the other way round: precision is good while recall is low. Precision/recall-curves are used to visualize this trade-off by plotting precision over recall for various threshold levels. The plots are sometimes also called *positive predictive value/sensitivity-plots*. An example is shown in Figure 5.

3.3 Receiver Operating Characteristic (ROC) and Area Under the Curve (AUC)

Similar to precision/recall curves, the receiver operating characteristic (ROC) curve (see Figure 6) plots the true positive rate versus false positive rate (sensitivity/recall versus “1–specificity” respectively) and therefore enables to assess the ability of a model to discriminate between failures and non-failures. The closer the curve gets to the upper left corner of the ROC space, the more accurate is the model.

As ROC curves accomplish for all thresholds, accuracy of prediction techniques can easily be evaluated by comparing their ROC curves: Area Under the Curve (AUC) is defined as the area between a ROC curve and the x-axis. It is calculated

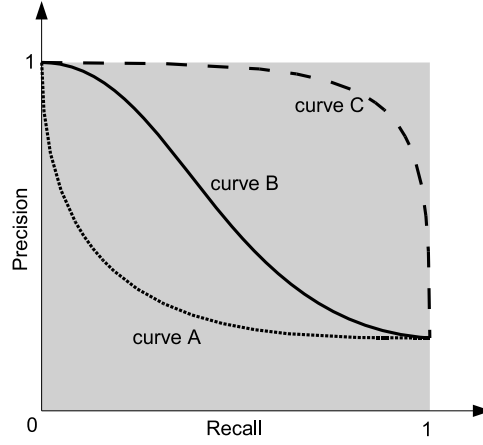


Fig. 5. Sample precision/recall-curves visualizing the trade-off between precision and recall. Curve A shows a predictor that is performing quite poorly: there is no point, where precision and recall simultaneously have high values. The failure prediction method pictured by curve B performs slightly better. Curve C reflects an algorithm whose predictions are mostly correct.

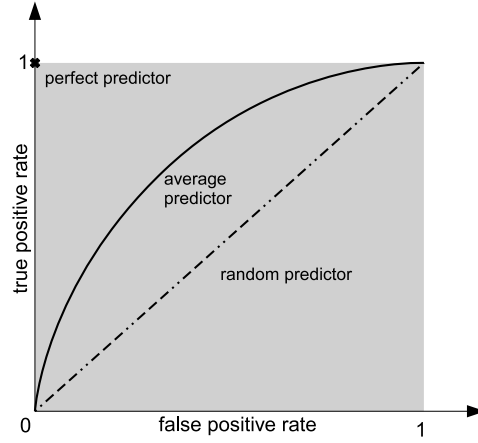


Fig. 6. Sample ROC plots. A perfect failure predictor shows a true positive rate of one and a false positive rate of zero. Many existing predictors facilitate to adjust the trade-off between true positive rate and false positive rate, as indicated by the solid line. The diagonal shows a random predictor: at each point the chance of a false or true positive prediction is equal.

as:

$$AUC = \int_0^1 tpr(fpr) dfpr \in [0, 1] \quad (8)$$

where tpr and fpr denote true positive rate and false positive rate, respectively. AUC is basically the probability that a data point of a failure-prone situation receives a higher score than a data point of a non failure-prone situation. As AUC turns the ROC curve into a single number by measuring the area under the ROC

curve, it summarizes the inherent capacity of a prediction algorithm to discriminate between failures and non-failures. A random predictor receives an AUC of 0.5 (the inversion is not always true, see, e.g., [Flach 2004]) while a perfect predictor results in an AUC of one.

3.4 Estimating the Metrics

In order to estimate the metrics discussed in this section, a reference data set is needed, for which it is known, when failures have occurred. In machine learning, this is called a “labeled data set.” Since the evaluation metrics are determined using statistical estimators the data set should be as large as possible. However, failures are in general rare events usually putting a natural limit to the number of failures in the data set.

If the online prediction method involves estimation of parameters from the data, the data set has to be divided into up to three parts:

- (1) *Training* data set: The data on which parameter optimization is performed.
- (2) *Validation* data set: In case the parameter optimization algorithm might result in local rather than global optima, or in order to control the so-called bias-variance trade-off, validation data is used to select the best parameter setting.
- (3) *Test* data set: Evaluation of failure prediction performance is carried out on data that has not been used to determine the parameters of the prediction method. Such evaluation is also called *out-of-sample* evaluation.

In order to determine the number of TP, FP, FN, and TN predictions required to fill out the contingency table and to subsequently compute metrics such as precision and recall, the prediction algorithm is applied to test data and prediction outcomes are compared to the true occurrence of failures. The four cases that can occur are depicted in Figure 7. As can be seen from the figure, prediction period Δt_p (c.f., Section 2.2) is used to determine whether a failure is counted as predicted or not. Hence, the choice of Δt_p impacts the contingency table and should be chosen in congruence with requirements for subsequent steps in proactive fault management.

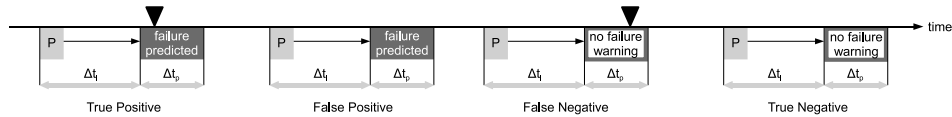


Fig. 7. A time line showing true failures of a test data set (▼) and all four types of predictions: TP, FP, FN, TN. A failure is counted as predicted if it occurs within a prediction period of length Δt_p , which starts lead-time Δt_l after beginning of prediction P .

In order to determine curves such as precision/recall curves or ROC plots, the predictors rating rather than the threshold-based binary decision should be stored, which enables to generate the curve for all possible threshold values using an algorithm such as described in [Fawcett 2004].

Estimating evaluation metrics from a finite set of test data only yields an approximate assessment of the prediction performance and should hence be accompanied

by confidence intervals. Confidence intervals are usually estimated by running the estimation procedure several times. Since this requires an enormous amount of data, techniques such as cross validation, jackknife or bootstrapping are applied. A more detailed discussion of such techniques can be found in [Salfner 2008, Chapter 8.4].

4. A TAXONOMY OF ONLINE FAILURE PREDICTION METHODS

A significant body of work has been published in the area of online failure prediction research. This section introduces a taxonomy of online failure prediction approaches in order to structure the manifold of approaches. In order to predict upcoming failures from measurements, the causing factors, which are faults, have to be made visible. As explained in Section 2, a fault can evolve into a failure through four stages: *fault*, *undetected error*, *detected error*, and *failure*, and it might cause side-effects which are called *symptoms*. Therefore, measurement-based failure prediction has to rely on capturing faults (see Figure 3):

- (1) In order to identify a fault, *testing* must be performed. The goal of testing is to identify flaws in a system regardless whether the entity under test is actually used by the system or not. For example, in memory testing, the entire memory is examined even though some areas might never be used.
- (2) Undetected errors can be identified by *auditing*. Auditing describes techniques that check whether the entity under audit is in an incorrect state. For example, memory auditing would inspect used data structures by checksumming.
- (3) Symptoms, which are side-effects of errors, can be identified by *monitoring* system parameters such as memory usage, workload, sequence of function calls, etc. An undetected error can be made visible by identifying out-of-norm behavior of the monitored system variable(s).
- (4) Once an error detector identifies an incorrect state the detected error may become visible by *reporting*. Reports are written to some logging mechanism such as logfiles or Simple Network Management Protocol (SNMP) messages.
- (5) Finally, the occurrence of failures can be made visible by *tracking* mechanisms. Tracking includes, for example, watching service response times or sending testing requests to the system for the purpose of monitoring.

The taxonomy introduced here is structured along the five stages of fault capturing. However, the focus of this article is *online* failure prediction, which means that short-term predictions are made on the basis of *runtime monitoring*. Hence, methods based on *testing* are not included since testing is not performed during runtime. *Auditing* of undetected errors can be applied offline as well as during runtime, which qualifies it for being included in the taxonomy. However, we have not found any publication investigating audit-based *online* failure prediction, and hence the branch has no further subdivisions. The full taxonomy is shown in Figure 8.

In Figure 8 the tree is split vertically into four major branches of the *type of input data* used, namely data from failure tracking, symptom monitoring, detected error reporting, and undetected error auditing. Each major branch is further divided vertically into *principal approaches*. Each principal approach is then horizontally divided into categories grouping the methods that we have surveyed. In this section

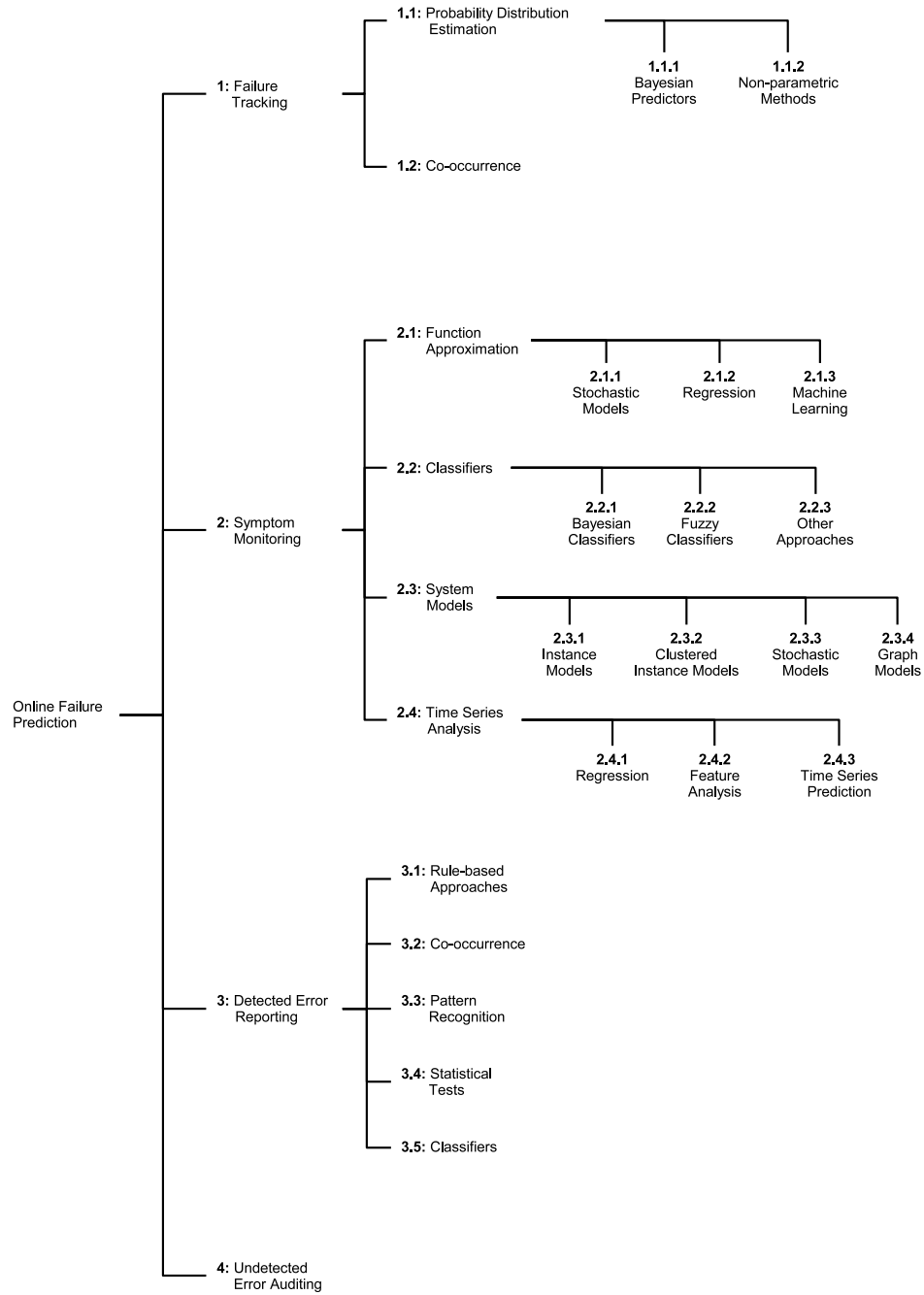


Fig. 8. A taxonomy for online failure prediction approaches.

we briefly describe the major categories (vertical splits), whereas details on the methods that are actually used (horizontal splits) are provided in Section 5.

Failure Tracking (1)

The basic idea of failure prediction based on failure tracking is to draw conclusions about upcoming failures from the occurrence of previous failures. This may include the time of occurrence as well as the types of failures that have occurred.

Probability Distribution Estimation (1.1). Prediction methods belonging to this category try to estimate the probability distribution of the time to the next failure from the previous occurrence of failures. Such approaches are in most cases rather formal since they have their roots in (offline) reliability prediction, even though they are applied during runtime.

Co-Occurrence (1.2). The fact that system failures can occur close together either in time or in space (e.g., at proximate nodes in a cluster environment) can be exploited to make an inference about failures that might come up in the near future.

Symptom Monitoring (2)

The motivation for analyzing periodically measured system variables such as the amount of free memory in order to identify an imminent failure is the fact that some types of errors affect the system even before they are detected (this is sometimes referred to as *service degradation*). A prominent example for this are memory leaks: due to the leak the amount of free memory is slowly decreasing over time, but, as long as there is still memory available, the error is neither detected nor is a failure observed. When memory is getting scarce, the computer may first slow down (e.g., due to memory swapping) and only if there is no memory left an error is detected and a failure might result. The key notion of failure prediction based on monitoring data is that errors like memory leaks can be grasped by their side-effects on the system such as exceptional memory usage, CPU load, disk I/O, or unusual function calls in the system. These side-effects are called symptoms. Symptom-based online failure prediction methods frequently address non-failstop failures, which are usually more difficult to grasp. Four principle approaches have been identified: Failure prediction based on function approximation, classifiers, a system model, and time series analysis.

Function Approximation (2.1). Function approximation techniques try to mimic a target value, which is supposed to be the output of an unknown function of measured system variables as input data (see Figure 9). For failure prediction the target function is usually either

- (1) the probability of failure occurrence. In this case, the target value is a boolean variable only available in the training data set but not during runtime. This case is depicted in Figure 9, or
- (2) some computing resource such as the amount of free memory. Although the current value is measurable during runtime, function approximation is used in order to extrapolate resource usage into the future and to predict the time of resource exhaustion.

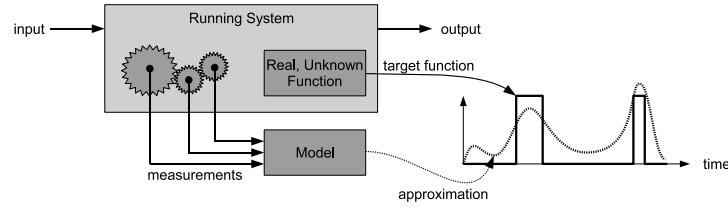


Fig. 9. Function approximation tries to mimic an unknown target function by the use of measurements taken from a system at runtime.

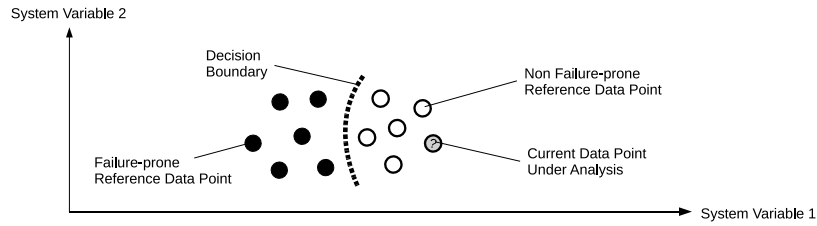


Fig. 10. Online failure prediction by classification of system variable observations. A decision boundary is determined from labeled reference data points (training data). During runtime, the current situation is judged to be failure-prone or not depending on which side of the decision boundary the current data point under analysis is.

Classifiers (2.2). Instead of approximating a target function, some failure prediction algorithms evaluate the current values of system variables directly. Failure prediction is achieved by classifying whether the current situation is failure-prone or not. The classifier’s decision boundary is usually derived from a reference data set for which it is known for each data point whether it indicates a failure-prone or non failure-prone situation. Online failure prediction during runtime is then accomplished by checking on which side of the decision boundary the current monitoring values are (see Figure 10). The dimensions of data points can be discrete or continuous values. For example, in hard disk failure prediction based on Self-Monitoring And Reporting Technology (SMART) values, input data may consist of the number of reallocated sectors (discrete value) and the drive’s temperature (theoretically continuous variable).

System Models (2.3). In contrast to the classifier approach, which requires training data for both the failure-prone and non failure-prone case, system model-based failure prediction approaches rely on modeling of failure-free behavior only, i.e., normal system behavior. The model is used to compute expected values, to which the current measured values are compared. If they differ significantly, system is suspected not to behave as normal and an upcoming failure is predicted (see Figure 11).

Time Series Analysis (2.4). As the name suggests, failure prediction approaches in this category treat a sequence of monitored system variables as a time series. This means that the prediction is based on an analysis of several successive samples

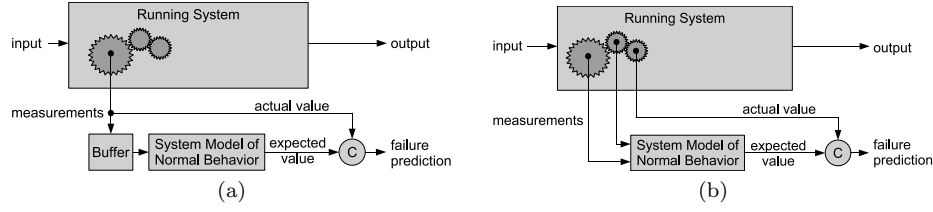


Fig. 11. Online failure prediction using a system model. Failure prediction is performed by comparison (C) of an expected value to an actual, measured value. The expected value is computed from a system model of normal behavior. The expected value is either computed from previous (buffered) monitoring values (a) or from other monitoring variables measured at the same time (b).

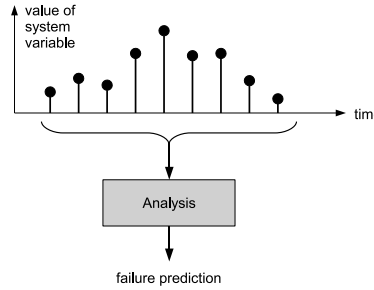


Fig. 12. Online failure prediction by time series analysis. Several successive measurements of a system variable are analyzed in order to predict upcoming failures.

of a system variable, as is shown in Figure 12. The analysis of the time series either involves computation of a residual value on which the current situation is judged to be failure-prone or not, or the future progression of the time series is predicted in order to estimate, e.g., time until resource exhaustion.

Detected Error Reporting (3)

When an error is detected, the detection event is usually reported using some logging facility. Hence, failure prediction approaches that use error reports as input data have to deal with event-driven input data. This is one of the major differences to symptom monitoring-based approaches, which in most cases operate on periodic system observations. Furthermore, symptoms are in most cases real-valued while error events mostly are discrete, categorical data such as event IDs, component IDs, etc. The task of online failure prediction based on error reports is shown in Figure 13: At present time t_0 , error reports that have occurred during some data window before t_0 are analyzed in order to decide whether there will be a failure at some point in time in the future.

Rule-based Systems (3.1). The essence of rule-based failure prediction is that the occurrence of a failure is predicted once at least one of a set of conditions is met.

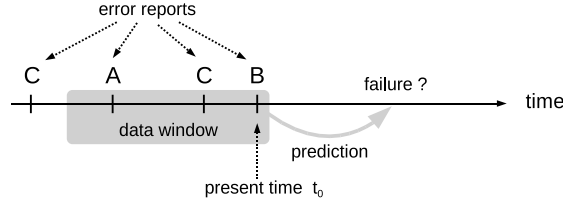


Fig. 13. Failure prediction based on the occurrence of error reports (A,B,C). The goal is to assess the risk of failure at some point in future. In order to perform the prediction, some data that have occurred shortly before present time t_0 are taken into account (data window).

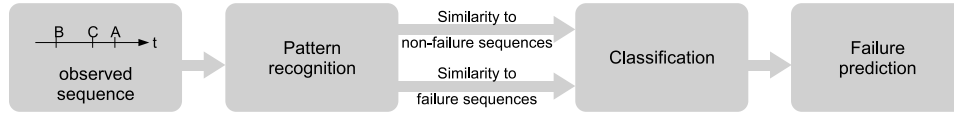


Fig. 14. Failure prediction by recognition of patterns in sequences of error reports.

Hence rule-based failure prediction has the form

IF $\langle condition_1 \rangle$ THEN $\langle failure\ warning \rangle$
 IF $\langle condition_2 \rangle$ THEN $\langle failure\ warning \rangle$
 ...

Since in most computer systems the set of conditions cannot be set up manually, the goal of failure prediction algorithms in this category is to identify the conditions algorithmically from a set of training data. The art is to find a set of rules that is general enough to capture as many failures as possible but that is also specific enough not to generate too many false failure warnings.

Co-occurrence (3.2). Methods that belong to this category analyze error detections that occur close together either in time or in space. The difference to Category 1.2 is that the analysis is based on detected errors rather than previous failures.

Pattern Recognition (3.3). Sequences of error reports form error patterns. The goal of pattern recognition-oriented failure prediction approaches is to identify patterns that indicate an upcoming failure. In order to achieve this, usually a ranking value is assigned to an observed sequence of error reports expressing similarity to patterns that are known to lead to system failures and to patterns that are known not to lead to a system failure. The final prediction is then accomplished by classification on basis of similarity rankings (see Figure 14).

Statistical Tests (3.4). The occurrence of error reports can be analyzed using statistical tests. For example, the histogram of number of error reports per component can be analyzed and compared to the “historically normal” distribution using a statistical test.

Classifiers (3.5). The goal of classification is to assign a class label to a given input data vector, which in this case is a vector of error detection reports. Since one single detected error is generally not sufficient to infer whether a failure is imminent or not, the input data vector is usually constructed from several errors reported within a time window.

Undetected Error Auditing (4)

In order to predict failures as early as possible, one can actively search for incorrect states (undetected errors) within a system. For example, the inode structure of a UNIX file system could be checked for consistency. A failure might then be predicted depending on the files that are affected by a file system inconsistency. The difference to detected error reporting (Category 3) is that auditing actively searches for incorrect states regardless whether the data is used at the moment or not, while error detection performs checks on data that is actually used or produced. However, as stated above, we have not found any failure prediction approaches that apply online auditing and hence the taxonomy contains no further subbranches.

5. SURVEY OF PREDICTION METHODS

In this survey, failure prediction methods are briefly described with appropriate reference to the source, and summarized in Table III. Representative selected methods are explained in greater detail in Appendices A–K.

Failure Tracking (1)

Two principal approaches to online failure prediction based on the previous occurrence of failures can be determined: estimation of the probability distribution of a random variable for time to the next failure, and approaches that build on the co-occurrence of failure events.

PROBABILITY DISTRIBUTION ESTIMATION (1.1). In order to estimate the probability distribution of the time to the next failure, Bayesian predictors as well as non-parametric methods have been applied.

Bayesian Predictors (1.1.1). The key notion of Bayesian failure prediction is to estimate the probability distribution of the next time to failure by benefiting from the knowledge obtained from previous failure occurrences in a Bayesian framework.

In Csenki [1990], such a Bayesian predictive approach [Aitchison and Dunsmore 1975] is applied to the Jelinski-Moranda software reliability model [Jelinski and Moranda 1972] in order to yield an improved estimate of the next time to failure probability distribution. Although developed for (offline) software reliability prediction, the approach could be applied in an online manner as well.

Non-parametric Methods (1.1.2). It has been observed that the failure process can be non-stationary and hence the probability distribution of time-between-failures (TBF) varies. Reasons for non-stationarity are manifold, since the fixing of bugs, changes in configuration or even varying utilization patterns can affect the failure process. In these cases, techniques such as histograms result in poor estimations since stationarity (at least within a time window) is inherently assumed. For these reasons, the non-parametric method of Pfefferman and Cernuschi-Frias

[2002] assumes the failure process to be a Bernoulli-experiment where a failure of type k occurs at time n with probability $p_k(n)$. From this assumption follows that the probability distribution of TBF for failure type k is geometric since only the n -th outcome is a failure of type k and hence the probability is:

$$\Pr\{TBF_k(n) = m \mid \text{failure of type } k \text{ at } n\} = p_k(n)(1 - p_k(n))^{m-1} \quad (9)$$

The authors propose a method to estimate $p_k(n)$ using an autoregressive averaging filter with a “window size” depending on the probability of the failure type k .

CO-OCCURRENCE (1.2). Due to sharing of resources, system failures can occur close together either in time or in space (at a closely coupled set of components or computers) (see, e.g., [Tang and Iyer 1993]). However, in most cases, co-occurrence has been analyzed for root cause analysis rather than failure prediction.

It has been observed several times, that failures occur in clusters in a temporal as well as in a spatial sense. Liang et al. [2006] choose such an approach to predict failures of IBM’s BlueGene/L from event logs containing reliability, availability and serviceability data. The key to their approach is data preprocessing employing first a categorization and then temporal and spatial compression: Temporal compression combines all events at a single location occurring with inter-event times lower than some threshold, and spatial compression combines all messages that refer to the same location within some time window. Prediction methods are rather straightforward: Using data from temporal compression, if a failure of type application I/O or network appears, it is very likely that a next failure will follow shortly. If spatial compression suggests that some components have reported more events than others, it is very likely that additional failures will occur at that location. Please refer to Appendix B for further details.

Fu and Xu [2007] further elaborate on temporal and spatial compression and introduce a measure of temporal and spatial correlation of failure events in distributed systems.

Symptom Monitoring (2)

Symptoms are side-effects of errors. In this section online failure prediction methods are surveyed that analyze monitoring data in order to detect symptoms that indicate an upcoming failure.

FUNCTION APPROXIMATION (2.1). Function approximation is a term used in a large variety of scientific areas. Applied to the task of online failure prediction, there is an assumed unknown functional relationship between monitored system variables (input to the function) and a target value (output of the function). The objective is to reveal this relationship from measurement data.

Stochastic Models (2.1.1). Vaidyanathan and Trivedi [1999] try to approximate the amount of swap space used and the amount of real free memory (target functions) from workload-related input data such as the number of system calls. They construct a semi-Markov reward model in order to obtain a workload-based estimation of resource consumption rate, which is then used to predict the time to resource exhaustion. In order to determine the states of the semi-Markov reward model, the input data is clustered. The authors assume that these clusters repre-

sent eleven different workload states. State transition probabilities were estimated from the measurement dataset and sojourn-time distributions were obtained by fitting two-stage-hyperexponential or two-stage-hypoexponential distributions to the training data. Then, a resource consumption “reward” rate for each workload state is estimated from the data: Depending on the workload state the system is in, the state reward defines at what rate the modeled resource is changing. The rate was estimated by fitting a linear function to the data using the method of Sen [Sen 1968]. Experiments have been performed on data recorded from a SunOS 4.1.3 workstation. Please refer to Appendix C for more details on the approach.

Li et al. [2002] collect various parameters such as used swap space from an Apache webserver and build autoregressive model with auxiliary input (ARX) to predict further progression of system resources utilization. Failures are predicted by estimating resource exhaustion times. They compared their method to [Castelli et al. 2001] (see Category 2.4.1) and showed that on their data set, ARX modeling resulted in much more accurate predictions.

Regression (2.1.2). In curve fitting, which is another name for regression, parameters of a function are adapted such that the curve best fits the measurement data, e.g., by minimizing mean square error. The simplest form of regression is curve fitting of a linear function.

Andrzejak and Silva [2007] apply deterministic function approximation techniques such as splines to characterize the functional relationships between the target function (the authors use the term “aging indicator”) and “work metrics” as input data. Work metrics are, e.g., the work that has been accomplished since the last restart of the system. Deterministic modeling offers a simple and concise description of system behavior with few parameters. Additionally, using work-based input variables rather than time-based offers the advantage that the function is not depending on absolute time anymore: For example, if there is only little load on a server, aging factors accumulate slowly and so does accomplished work whereas in case of high load, both accumulate more quickly. The authors present experiments where performance of an Apache Axis SOAP (Simple Object Access Protocol) server has been modeled as a function of various input data such as requests per second or the percentage of CPU idle time.

Machine Learning (2.1.3). Function approximation is one of the predominant applications of machine learning. It seems natural that various techniques have a long tradition in failure prediction, as can also be seen from various patents in that area. Troudet et al. [1990] have proposed to use neural networks for failure prediction of mechanical parts and Wong et al. [1996] use neural networks to approximate the impedance of passive components of power systems. The authors have used an RLC-II model, which is a standard electronic circuit consisting of a two resistors (R), an inductor (L), and two capacities (C), where faults have been simulated to generate the training data. Neville [1998] has described how standard neural networks can be used for failure prediction in large scale engineering plants.

Turning to publications regarding failure prediction in large scale computer systems, various techniques have been applied there, too.

In [Hoffmann 2006], the author has developed a failure prediction approach based

on universal basis functions (UBF), which are an extension to radial basis functions (RBF) that use a weighted convex combination of two kernel functions instead of a single kernel. UBF approximation has been applied to predict failures of a telecommunication system. In [Hoffmann et al. 2007], the authors have conducted a comparative study of several modeling techniques with the goal to predict resource consumption of the Apache webserver. The study showed that UBF turned out to yield the best results for free physical memory prediction, while server response times could be predicted best by support vector machines (SVM). Appendix D provides further details on UBF-based failure prediction.

One of the major findings in [Hoffmann et al. 2007] is that the issue of choosing a good subset of input variables has a much greater influence on prediction accuracy than the choice of modeling technology. This means that the result might be better if, for example, only workload and free physical memory are taken into account and other measurements such as used swap space are ignored. *Variable selection* (some authors also use the term *feature selection*) is concerned with finding the optimal subset of measurements. Typical examples of variable selection algorithms are principle component analysis (PCA, see [Hotelling 1933]) as used in [Ning et al. 2006] or Forward Stepwise Selection (see, e.g., [Hastie et al. 2001, Chapter 3.4.1]), which has been used in [Turnbull and Alldrin 2003]. In addition to UBF, Hoffmann [2006] has also developed a new algorithm called *probabilistic wrapper approach* (PWA), which combines probabilistic techniques with forward selection or backward elimination.

Instance-based learning methods store the entire training dataset including input and target values and predict by finding similar matches in the stored database of training data (eventually combining them). Kapadia et al. [1999] have applied three learning algorithms (k-nearest-neighbors, weighted average and weighted polynomial regression) to predict CPU-time of the semiconductor manufacturing simulation software T-Suprem3 based on input parameters to the software such as minimum implant energy or number of etch steps in the simulated semiconductor manufacturing process.

Fu and Xu [2007] build a neural network to approximate the number of failures in a given time interval. The set of input variables consists of a temporal and spatial failure correlation factor together with variables, such as CPU utilization or the number of packets transmitted by a computing node. The authors use (not further specified) neural networks. Data of one year of operation of the Wayne State University Grid has been analyzed as a case study. Due to the fact that a correlation value of previous failures is used as input data as well, this prediction approach also partly fits into Category 1.2.

In the paper by Abraham and Grosan [2005] the target function is the so-called stressor-susceptibility-interaction (SSI), which basically denotes failure probability as function of external stressors such as environment temperature or power supply voltage. The overall failure probability can be computed by integration of single SSIs. The paper presents an approach where genetic programming has been used to generate code representing the overall SSI function from training data of an electronic device's power circuit.

CLASSIFIERS (2.2). Failure prediction methods in this category build on classifiers that are trained from failure-prone as well as non failure-prone data samples.

Bayesian Classifiers (2.2.1). In [Hamerly and Elkan 2001] two Bayesian failure prediction approaches are described. The first Bayesian classifier proposed by the authors is abbreviated by NBEM expressing that a specific Naïve Bayes model is trained with the Expectation Maximization algorithm based on a real data set of SMART values of Quantum Inc. disk drives. Specifically, a mixture model is proposed where each naïve Bayes submodel m is weighted by a model prior $P(m)$ and an expectation maximization algorithm is used to iteratively adjust model priors as well as submodel probabilities. Second, a standard naïve Bayes classifier is trained from the same input data set. More precisely, SMART variables x_i such as read soft error rate or number of calibration retries are divided into bins. The term “naïve” derives from the fact that all attributes x_i in the current observation vector \vec{x} are assumed to be independent and hence the joint probability $P(\vec{x} | c)$ can simply be computed as the product of single attribute probabilities $P(x_i | c)$. The authors report that both models outperform the rank sum hypothesis test failure prediction algorithm of Hughes et al. [2002]⁴ (see Category 2.3.1). Please refer to Appendix E for more details on these methods. In a later study [Murray et al. 2003], the same research group has applied two additional failure prediction methods: support vector machines (SVM) and an unsupervised clustering algorithm. The SVM approach is assigned to Category 2.2.2 and the clustering approach belongs to Category 2.3.2.

Pizza et al. [1998] propose a method to distinguish (i.e., classify) between transient and permanent faults: whenever erroneous component behavior is observed (e.g., by component testing) the objective is to find out whether this erroneous behavior was caused by a transient or permanent fault. Although not mentioned in the paper, this method could be used for failure prediction. For example, a performance failure of a grid computing application might be predicted if the number of permanent grid node failures exceeds a threshold (under the assumption that transient outages do not affect overall grid performance severely). This method enables to decide whether a tested grid node has a permanent failure or not.

Fuzzy Classifier (2.2.2). Bayes classification requires that input variables take on discrete values. Therefore, monitoring values are frequently assigned to finite number of bins (as, for example, in [Hamerly and Elkan 2001]). However, this can lead to bad assignments if monitoring values are close to a bin’s border. Fuzzy classification addresses this problem by using probabilistic class membership.

Turnbull and Alldrin [2003] use Radial Basis Functions networks (RBFN) to classify monitoring values of hardware sensors such as temperatures and voltages on motherboards. More specifically, all N monitoring values occurring within a data window are represented as a feature vector which is then classified to belong to a failure-prone or non failure-prone sequence using RBFNs. Experiments were conducted on a server with 18 hot-swappable system boards with four processors, each. The authors achieve good results, but failures and non-failures were equally

⁴Although the paper [Hughes et al. 2002] appeared after [Hamerly and Elkan 2001] it was announced and submitted already in 2000.

likely in the data set.

Berenji et al. [2003] use an RBF rule base to classify whether a component is faulty or not: Using Gaussian rules, a so-called diagnostic model computes a diagnostic signal based on input and output values of components ranging from zero (fault-free) to one (faulty). The rule base is algorithmically derived by means of clustering of training data, which consists of input / output value pairs both for the faulty as well as fault-free case. The training data is generated from so-called component simulation models that try to mimic the input / output behavior of system components (fault-free and faulty). The same approach is then applied on the next hierarchical level to obtain a system-wide diagnostic models. The approach has been applied to model a hybrid combustion facility developed at NASA Ames Research Center. The diagnostic signal can be used to predict slowly evolving failures.

Murray et al. [2003] have applied SVMs in order to predict failures of hard disk drives. SVMs have been developed by Vapnik [1995] and are powerful and efficient neural network classifiers. In the case of hard disk failure prediction, five successive samples of each selected SMART attribute set up the input data vector. The training procedure of SVMs adapts the classification boundary such that the margin between the failure-prone and non failure-prone data points becomes maximal. Although the naïve Bayes approach developed by the same group (see [Hughes et al. 2002], Category 2.3.1) is mentioned in the paper, no comparison has been carried out.

In [Bodík et al. 2005] hit frequencies of web-pages are analyzed in order to quickly identify non-failstop failures in the operation of a big commercial web site. The authors use a naïve Bayes classifier. Following the same pattern as described in Category 2.2.1, the probability $P(k | \vec{x})$, where k denotes the class label (normal or abnormal behavior) and \vec{x} denotes the vector of hit frequencies, is computed from likelihoods $P(x_i | k)$ which are approximated by Gaussian distributions. Since the training data set was not labeled (it was not known when failures had occurred) likelihoods for the failure case were assumed to be uniformly distributed and unsupervised learning techniques had to be applied. The output of the naïve Bayes classifier is an anomaly score. In the paper, a second prediction technique based on a χ^2 test is proposed which is described in Category 2.3.1.

Another valuable contribution of this work is a successful combination of anomaly detection and detailed analysis support in form of a visual tool.

Other approaches (2.2.3). In a joint effort University of California Berkeley and Stanford University have developed a computing approach called “recovery-oriented computing.” As main references, see [Brown and Patterson 2001; Patterson et al. 2002] for an introduction and [Candea et al. 2003; Candea et al. 2006] for a description of “JAGR” (JBoss with Application Generic Recovery), which combines several of the techniques to build a dependable system. Although primarily targeted towards a quick detection and analysis of failures after their occurrence, several techniques could be used for failure prediction as well. Hence, in this survey runtime path-based methods are included, which are “Pinpoint” (Category 2.3.1), path modeling using probabilistic context free grammars (Category 2.3.3), component peer models (Category 2.3.4), and decision trees, which belong to this category.

Kiciman and Fox [2005] propose to construct a decision tree from runtime paths in order to identify faulty components. The term runtime path denotes the sequence of components and other features such as IP addresses of server replicas in the cluster, etc. that are involved in handling one request in a component-based software such as a J2EE application server. Runtime paths are obtained using Pinpoint (see Category 2.3.1). Having recorded a sufficiently large number of runtime paths including failed and successful requests, a *decision tree* for classifying requests as failed or successful is constructed using algorithms such as ID3 or C4.5. Although primarily designed for diagnosis, the authors point out that the approach could be used for failure prediction of single requests as well.

Daidone et al. [2006] have proposed to use a hidden Markov model approach to infer whether the true state of a monitored component is healthy or not. Since the outcome of a component test does not always represent its true state, hidden Markov models are used where observation symbols relate to outcomes of component probing, and hidden states relate to the (also hidden) component's true state. The true state (in a probabilistic sense) is inferred from a sequence of probing results by the so-called forward algorithm of hidden Markov models. Although not intended by the authors, the approach could be used for failure prediction in the following way: Assuming that there are some erroneous states in a system that lead to future failures and others that do not, the proposed hidden Markov model approach can be used to determine (classify) whether a failure is imminent or not on the basis of probing.

SYSTEM MODELS (2.3). Online failure prediction approaches belonging to this category utilize a model of failure free, normal system behavior. The current, measured system behavior is compared to the expected normal behavior and a failure is predicted in case of a significant deviation. We have categorized system model-based prediction approaches according to how normal behavior is stored: as instances, by clustered instances, using stochastic descriptions, or using formalisms known from control theory.

Instance Models (2.3.1). The most straightforward data-driven way to memorize how a system behaves normally is to store monitoring values recorded during failure-free operation. If the current monitoring values are not similar to any of the stored values, a failure is predicted.

Elbaum et al. [2003] have carried out experiments where function calls, changes in the configuration, module loading, etc. of the email client “pine” had been recorded. The authors have proposed three types of failure prediction among which sequence-based checking was most successful: a failure was predicted if two successive events occurring in “pine” during runtime do not belong to any of the event transitions in the stored training data.

Hughes et al. [2002] apply a simple albeit robust statistical test for hard disk failure prediction. The authors employ a rank sum hypothesis test to identify failure prone hard disks. The basic idea is to collect SMART values from fault-free drives and store them as reference data set. Then, during runtime SMART values of the monitored drive are tested the following way: The combined data set consisting of the reference data and the values observed at runtime is sorted and

the ranks of the observed measurements are computed⁵. The ranks are summed up and compared to a threshold. If the drive is not fault-free, the distribution of observed values are skewed and the sum of ranks tends to be greater or smaller than for fault-free drives.

Pinpoint [Chen et al. 2002] tracks requests to a J2EE application server on their way through the system in order to identify the software components that are correlated with a failure. Tracking of the requests yields a set of components used to process the request. In case of a failure, the sets of components for several requests are clustered using a Jaccard score-based metric measuring similarity of the sets. A similar approach could be applied for online failure prediction. If several sets of failure-free request paths were stored, the same distance metric could be used to determine wheater the current set of components is similar to any of the known sets, and if not a failure is supposed to be imminent.

In [Bodík et al. 2005], which has been described in Category 2.2.2, a second detection / prediction technique has been applied to the same data: The current hit frequencies of the 40 most frequently used pages were compared to previous, “historically normal” hit frequencies of the same pages using a χ^2 -test. If the two distributions are different with a significance level of 99%, the current observation period is declared anomalous. In addition to this binary decision an anomaly score was assigned to each page in order to support quick diagnosis. The results achieved using the χ^2 -test are comparable to those of the naïve Bayes approach described in Category 2.2.2.

Clustered Instance Models (2.3.2). If the amount of storage needed for instance system models exceeds a reasonable level or if a more general representation of training instances is required, training instances can be clustered. In this case only cluster centroids or the boundaries between clusters need to be stored.

In a follow-up comparative study to [Hughes et al. 2002] (see Category 2.3.1), Murray et al. [2003] have introduced a clustering-based failure predictor for hard disk failure prediction. The basic idea is to identify areas of SMART values where a failure is very unlikely using unsupervised clustering. In other words, all areas of SMART values where the disk operates normally are algorithmically identified from failure-free training data. In order to predict an upcoming failure, the current SMART values are assigned to the most likely cluster. If they do not fit any known cluster (more specifically, maximum class membership probability is below a given threshold), the disk is assumed not to behave normally and a failure is assumed to be imminent.

Stochastic Models (2.3.3). Especially in the case of complex and dynamic systems, it seems appropriate to store system behavior using stochastic tools such as probability distributions.

Ward et al. [1998] estimate mean and variance of the number of TCP connections from two web proxy servers in order to identify Internet service performance failures. Using a statistical test developed by Pettitt [1977], the values is compared to previous number of connections at the same time of the day (holidays are treated separately). If the current value deviates significantly, a failure is predicted.

⁵which in fact only involves simple counting

In [Chen et al. 2004]⁶ a runtime path analysis technique based on probabilistic context free grammars (PCFG) is proposed. Probabilistic context-free grammars have been developed in the area of statistical natural language processing (see, e.g., [Manning and Schütze 1999, Page 381]). The notion of the approach is to build a grammar of all possible non faulty sequences of components. By assigning a probability to each grammar rule, the overall probability of a given sequence of components can be computed. From this an anomaly score is computed and if a sufficiently large amount of paths (i.e., requests) have a high anomaly score, a failure is assumed. The approach has been applied to call paths collected from a Java 2 Enterprise Edition (J2EE) demo application, an industrial enterprise voice application network, and from eBay servers. Although not intended by the authors, the same approach could be used to predict, e.g., service level failures: if a significant amount of requests do not seem to behave normally, the system might not be able to deliver the required level of service shortly in the future. It might also be applicable for request failure prediction: if the probability of the beginning of a path is very low, there is an increased probability that a failure will occur in the further course of the request.

Graph Models (2.3.4). In [Kiciman and Fox 2005], a second approach is proposed that is based on component interaction graphs (a so-called peer model). The peer model reflects how often one component interacts with another component: each component is a node and the amount how often one component interacts with the other is expressed by weighted links. One specific instance of a component is checked whether it is error-free by using a χ^2 goodness-of-fit test: if the proportion of runtime paths between a component instance and other component classes deviates significantly from the reference model representing fault-free behavior, the instance is suspected to be faulty. By adding a trend analysis on anomaly score, a future failure of the component instance might be predicted.

Control Theory Models (2.3.5). It is common in control theory to have an abstraction of the controlled system estimating the internal state of the system and its progression over time by some mathematical equations, such as linear equation systems, differential equation systems, Kalman filters, etc. (see, e.g., [Lunze 2003, Chapter 4]). These methods are widely used for fault diagnosis (see, e.g., [Korbicz et al. 2004, Chapters 2 and 3]) but have only rarely been used for failure prediction. However, many of the methods inherently include the possibility to predict future behavior of the system and hence have the ability to predict failures. For example, Neville [1998] describes in his Ph.D. thesis the prediction of failures in large scale engineering plants. Another example is Discenzo et al. [1999] who mention that such methods have been used to predict failures of an intelligent motor using the standard IEEE motor model.

With regard to online failure prediction, Singer et al. [1997] propose the Multivariate State Estimation Technique (MSET) to detect system disturbances by a comparison of the estimated and measured system state. More precisely, a matrix D of selected measurement data of normal operation is collected. In the operational phase, a state estimation is computed as a combination of D and the current

⁶The same approach is described in more detail in [Kiciman and Fox 2005]

(runtime) observations. The difference between observed and estimated state constitutes a residual that is checked for significant deviation by a sequential probability ratio test (SPRT). In [Gross et al. 2002], the authors have applied the method to detect software aging [Parnas 1994] in an experiment where a memory-leak fault injector consumed system memory at an adjustable rate. MSET and SPRT have been used to detect whether the fault injector was active and if so, at what rate it was operating. By this, time to memory consumption can be estimated. MSET has also been applied to online transaction processing servers in order to detect software aging [Cassidy et al. 2002].

Other potential approaches. A more theoretic approach that could in principle be applied to online failure prediction is to abstract system behavior by a queuing model that incorporates additional knowledge about the current state of the system. Failure prediction can be performed by computing the input value dependent expected response time of the system. Ward and Whitt [2000] show how to compute estimated response times of an M/G/I processor-sharing queue based on measurable input data such as number of jobs in the system at time of arrival using a numerical approximation of the inverse Laplace transform.

TIME SERIES ANALYSIS (2.4). We have identified four groups of methods that perform time series analysis: Regression tries to fit a function to the data, feature analysis computes a residual of the measurement series, time series prediction tries to predict the future progression of the target function from the series' values itself (without using other measurements as input data), and finally, also signal processing techniques can be used for time series analysis.

Regression (2.4.1). Similar to Category 2.1.2, regression techniques adjust parameters of a function such that it best fits some set of training data. However, in this section the function is fit directly into the sequence of monitored values, whereas in Category 2.1.2, some target function needs to be fit.

Garg et al. [1998] have presented a three step approach to compute time to resource exhaustion. First, the time series of monitored values is smoothed using robust locally weighted regression [Cleveland et al. 1979]. In order to detect, whether a trend is present or not, a seasonal Kendall test is applied since this statistic test can detect trends even in the presence of cycles. If a trend is detected, the rate of resource consumption is estimated using a non-parametric procedure developed by Sen [Sen 1968]. Experiments have been performed on measurements of system variable “real memory free”, size of file table, process table size, and used swap space of UNIX machines.

Castelli et al. [2001] mention that IBM has implemented a curve fitting algorithm for the xSeries Software Rejuvenation Agent. Several types of curves are fit to the measurement data and a model-selection criterion is applied in order to choose the best curve. Prediction is again accomplished by extrapolating the curve.

Cheng et al. [2005] present a two step approach for failure prediction in a high availability cluster system. Failure prediction is accomplished in two stages: first, a health index $\in [0, 1]$ is computed using fuzzy logic, and in case of a detected “sick” state of a node, a linear function is mapped to the monitored values of the resource in order to estimate mean time to resource exhaustion. The authors also

reference a technique called “prediction interval” to compute a lower and upper bound for time to resource exhaustion. The fuzzy logic assignment of the health index is based on “processor time”, “privileged time”, “pool nonpaged bytes”, and “available Mbytes” (presumably of free memory).

Feature Analysis (2.4.2). The goal of feature analysis is to compute a residual value from the time series upon which the decision whether a failure is imminent or not can be based.

Crowell et al. [2002] have discovered that memory related system parameters such as kernel memory or system cache resident bytes show multifractal characteristics in the case of software aging. The authors used the Hölder exponent to identify fractality, which is a residual expressing the amount of fractality in the time series. In a later paper [Shereshevsky et al. 2003], the same authors extended this concept and built a failure prediction system by applying the Shewhart change detection algorithm [Basseville and Nikiforov 1993, Page 31] to the residual time series of Hölder exponents. A failure warning is issued after detection of the second change point. Experiments have been performed on two machines running the “System Stress for Windows NT 4.0 and Windows 2000” provided by Microsoft. The algorithm was applied to several memory-related variables in order to predict system crashes.

Time Series Prediction (2.4.3). In [Hellerstein et al. 1999], the authors describe an approach to predict if a time series will violate a threshold. In order to achieve this, several time series models are employed to model stationary as well as non-stationary effects. For example, the model accounts for the influence of the day-of-the-week, or time-of-the-day, etc. Experiments have been carried out on prediction of HTTP operations per second of a production webserver. A similar approach has been described in [Vilalta et al. 2002]. In Appendix F a more detailed description of this method can be found.

Sahoo et al. [2003] applied various time series models to data of a 350-node cluster system to predict parameters like percentage of system utilization, idle time and network IO.

A relatively new technique on the rise is based on “rough set theory” [Pawlak et al. 1988], which is an approximation of conventional sets by providing a set of upper and lower values. Meng et al. [2007] combine rough set theory with wavelet networks in order to predict memory usage of a J2EE application server. In the experiments memory usage has been monitored every twelve minutes and the next monitoring value is predicted based on a series of previous monitoring values. From this one step ahead prediction of the monitoring variable follows that the lead time Δt_l equals the monitoring period (twelve minutes in this case). The same authors have published a similar paper about a combination of fuzzy logic and wavelet networks [Ning et al. 2006], which are called fuzzy wavelet networks (FWN) [Ho et al. 2001].

Other potential approaches. Signal processing techniques are of course related to methods that have already been described (e.g., Kalman filters in Category 2.3.5). Algorithms that fall into this category use signal processing techniques such as low-pass or noise filtering to obtain a clean estimate of a system resource measurement.

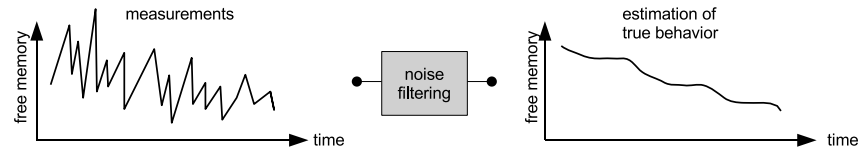


Fig. 15. Failure prediction using signal processing techniques on measurement data.

For example, if free system memory is measured, observations will vary greatly due to allocation and freeing of memory. Such measurement series can be seen as a noisy signal where noise filtering techniques can be applied in order to obtain the “true” behavior of free system memory: If it is a continuously decreasing function, software aging is likely in progress and the amount of free memory can be estimated for the near-future by means of signal processing prediction methods such as low-pass filtering or frequency transformation (see Figure 15).

Detected Error Reporting (3)

There are two main groups of failure prediction approaches that analyze error reports: rule-based or error pattern-based approaches.

RULE-BASED APPROACHES (3.1). Failure prediction methods in this category derive a set of rules where each rule consists of error reports.

To our knowledge, the first rule-based approach to failure prediction based on reported error events has been published by Hätönen et al. [1996]. The authors describe a system that identifies episode rules from error logs (the authors use the term *alarm*). Episode rules express temporal ordering of events in the form “if errors A and B occur within five seconds, then error C occurs within 30 seconds with probability 0.8”. Several parameters such as the maximum length of the data window, types of error messages, and ordering requirements had to be pre-specified. However, the algorithm returned too many rules such that they had to be presented to human operators with system knowledge in order to filter out informative ones.

Weiss [1999] introduces a failure prediction technique called “timeweaver” that is based on a genetic training algorithm. In contrast to searching and selecting patterns that exist in the database, rules are generated “from scratch” by use of a simple language: error events are connected with three types of ordering primitives. The genetic algorithm starts with an initial set of rules (initial population) and repetitively applies crossing and mutation operations to generate new rules. Quality of the obtained candidates is assessed using a special fitness function that incorporates both prediction quality (based on a variant of the F-Measure, that allows to adjust the relative weight of precision and recall) as well as diversity of the rule set. After generating a rule set with the genetic algorithm, the rule set is pruned in order to remove redundant patterns. The approach was applied to telecommunication equipment failure data and results are compared to three standard machine learning algorithms: C4.5rules [Quinlan 1993], RIPPER [Cohen 1995] and FOIL [Quinlan 1990]. Please refer to Appendix G for further details on timeweaver.

Vilalta and Ma [2002] describe a data-mining approach that is tailored to short-

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term prediction of boolean data building on a concept termed *eventsets*. The method searches for predictive subsets of events occurring prior to a target event. In the terminology used here, events refer to error reports and target events to failures. The method addresses the issue of class skewness (failures occur very rarely in comparison to non-failure events) by first considering only failure-prone sequences, and by incorporating non failure-prone data in a later step. More precisely, the method is divided into three steps: First, frequent subsets of error events preceding a failure are extracted. Second, subsets that occur frequently before failures but also frequently when no failure occurs are removed by a threshold on confidence and by applying a statistical test. In a final third step, overly general sets are removed. Please refer to Appendix H for further details on this approach. The eventset method has been applied for failure prediction in a 350-node cluster system, as described in [Sahoo et al. 2003] (Category 2.4.3).

Other potential approaches. Fault trees have been developed in the 1960's and have become a standard tool reliability modeling. A comprehensive treatment of fault trees is, for example, given by Vesely et al. [1981]. The purpose of fault trees is to model conditions under which failures can occur using logical expressions. Expressions are arranged in form of a tree, and probabilities are assigned to the leaf nodes, facilitating to compute the overall failure probability. Fault tree analysis is a static analysis that does not take the current system status into account. However, if the leaf nodes are combined with online fault detectors, and logical expressions are transformed into a set of rules, they can be used as a rule-based online failure predictor. Although such approach has been applied to chemical process failure prediction [Ulerich and Powers 1988] and power systems [Rovnyak et al. 1994], we have not found such approach being applied to computer systems.

Bai et al. [2005] employ a Markov Bayesian Network for reliability prediction but a similar approach might work for online failure prediction, as well. The same holds for decision tree methods: upcoming failures can be predicted if error events are classified using a decision tree approach similar to [Kiciman and Fox 2005] (see Category 2.2.3). In this case however, the decision tree would have to classify error reports rather than monitored runtime paths.

Regarding data mining, several developments could potentially be used to further improve data mining-based online failure prediction: Sequential pattern mining and the use of ontologies, as described in, e.g., [Srikant and Agrawal 1996], or path traversal patterns (see, e.g., [Chen et al. 1998]), which could be applied in transaction-based systems.

CO-OCCURRENCE (3.2). Levy and Chillarege [2003] analyze data of a industrial voice mail system and have identified three characteristics that they call “principles”, two of which support the assumptions on which failure prediction approaches in this category are based: principle one (“counts tell”) again emphasizes the property that the number of errors (since the paper is about a telecommunication system, the authors use the term *alarm* for what is termed an *error*, here) per time unit increases before a failure. Principle number two (“the mix changes”) is described in Category 3.4. Principle number three (“clusters form early”) basically states the same as principle one by putting more emphasis on the fact that for common

failures the effect is even more apparent if errors are clustered into groups. Similar observations have been made by Liang et al. [2006]: The authors have analyzed jobs of an IBM BlueGene/L supercomputer and support the thesis: “On average, we observe that if a job experiences two or more non-fatal events after filtering, then there is a 21.33% chance that a fatal failure will follow. For jobs that only have one non-fatal event, this probability drops to 4.7%”.

According to [Siewiorek and Swarz 1998, Page 262], Nassar and Andrews [1985] were one of the first to propose two ways of failure prediction based on the occurrence of error reports. The first approach investigates the distribution of error types. If the distribution of error types changes systematically (i.e., one type of error occurs more frequently) a failure is supposed to be imminent. The second approach investigates error distributions for all error types obtained for intervals between crashes. If the error generation rate increases significantly, a failure is looming. Both approaches resulted in computation of threshold values upon which a failure warning can be issued.

The dispersion frame technique (DFT) developed by Lin and Siewiorek [1990] uses a set of heuristic rules on the time of occurrence of consecutive error events of each component to identify looming permanent failures. A detailed description of the DFT can be found in Appendix I.

Lal and Choi [1998] show plots and histograms of errors occurring in a UNIX Server. The authors propose to aggregate errors in an approach similar to tupling (c.f., [Tsao and Siewiorek 1983]) and state that the frequency of clustered error occurrence indicates an upcoming failure. Furthermore, they showed histograms of error occurrence frequency over time before failure.

More recently, Leangsuksun et al. [2004] have presented a study where hardware sensors measurements such as fan speed, temperature, etc. are aggregated using several thresholds to generate error events with several levels of criticality. These events are analyzed in order to eventually generate a failure warning that can be processed by other modules. The study was carried out on data of a high availability high performance Linux cluster.

PATTERN RECOGNITION (3.3). Pattern recognition techniques operate on sequences of error events trying to identify patterns that indicate a failure-prone system state.

Methods such as eventset [Vilalta et al. 2002] investigate the type of error reports (e.g., the error message ID) while methods such as dispersion frame technique [Lin and Siewiorek 1990] focus on the time when errors are detected. If both parts of error reports –time and type– are considered together, the sequence of error reports turns into a temporal sequence. Salfner et al. have proposed two failure prediction methods that identify patterns in temporal sequences.

In [Salfner et al. 2006], the authors present Similar Events Prediction (SEP), which is a semi-Markov chain model. Each error report event corresponds to a state in the semi-Markov chain while time between two reports is represented by the continuous-time state transition duration of the semi-Markov chain using uniform distributions. Sequence similarity is computed by the product of state traversal probabilities. Training of the model involves hierarchical clustering of error sequences leading to a failure and computation of relative frequencies to estimate

state transition probabilities. The work includes experiments with data from an industrial telecommunication system.

In Salfner and Malek [2007] the authors propose to use hidden semi-Markov models (HSMM) in order to add one additional level of flexibility. Associating error detections with observations that are generated by the states of the HSMM, errors may be mapped to groups of hidden states. With HSMMs, similarity of error sequences can be computed by use of the forward algorithm, which is an efficient dynamic programming algorithm to compute the sequence likelihood. One advantage of HSMMs in comparison to [Salfner et al. 2006] is that HSMMs can handle permutations in the input event sequences. In addition to the classification step depicted in Figure 14, which is an evaluation of failure probability for some fixed point in time in the future, failure prediction can also be accomplished by computing the time-to-failure distribution (c.f., Salfner [2006]). Salfner [2008] provides more details on the HSMM method including a comparative analysis of HSMM with DFT, eventset method, and SVD-SVM (see Category 3.5). The study also includes a comparison of computational overhead both for training and application of the methods.

Other potential approaches. Computing similarity between sequences is one of the key tasks in biological sequence analysis [Durbin et al. 1998, Chapter 2], which is called *pairwise alignment*. Various algorithms have been developed such as the Needleman-Wunsch algorithm [Needleman and Wunsch 1970], Smith-Waterman algorithm [Smith and Waterman 1981] or the BLAST algorithm [Altschul et al. 1990]. The outcome of such algorithms is usually a score evaluating the alignment of two sequences. If used as a similarity measure between the sequence under investigation and known failure sequences, failure prediction can be accomplished as depicted in Figure 14. One of the advantages of alignment algorithms is that they build on a substitution matrix providing scores for the substitution of symbols. In terms of error event sequences this technique has the potential to define a score for one error event being “replaced” by another event giving rise to use a hierarchical grouping of errors as proposed in [Salfner et al. 2004].

In Category 2.3.3 the paper by Kiciman and Fox [2005] was described who used probabilistic context-free grammars (PCFG) to analyze runtime paths. However, runtime paths contain symptoms rather than errors. Nevertheless, PCFGs could also be used to perform error report-based failure prediction: Following the approach depicted in Figure 14, PCFGs can be used to compute sequence similarity to error report sequences that have lead to a failure in the training dataset, and to compute sequence similarity to error report sequences that usually do not lead to a failure.

A further well-known stochastic speech modeling technique are *n-gram models* [Manning and Schütze 1999, Page 192]. *n*-grams represent sentences by conditional probabilities taking into account a context of up to *n* words in order to compute the probability of a given sentence.⁷ Conditional densities are estimated from training

⁷Although, in most applications of statistical natural language processing the goal is to predict the next word using $P(w_n|w_1, \dots, w_{n-1})$, the two problems are connected via the theorem of conditional probabilities.

data. Transferring this concept to failure prediction, error events correspond to words and error sequences to sentences. If the probabilities (the “grammar”) of an n -gram model were estimated from failure sequences, high sequence probabilities would translate into “failure-prone” and low probabilities into “not failure-prone”.

STATISTICAL TESTS (3.4). Principle number two (“the mix changes”) in [Levy and Chillarege 2003] mentioned in Category 3.2 delineates the discovery that the order of subsystems sorted by error generation frequency changes prior to a failure. According to the paper, relative error generation frequencies of subsystems follow a Pareto distribution: Most errors are generated by only a few subsystems while most subsystems generate only very few errors (which is also known as Zipf’s law [Zipf 1949]). The proposed failure prediction algorithm monitors the order of subsystems and predicts a failure if it changes significantly, which basically is a statistical test. Using data of the voice mail application analyzed, the authors show examples where the change in order can be observed, however no results with respect to false negatives or false positives are reported.

CLASSIFIERS (3.5). Classifiers usually associate an input vector with a class label. In this Category 3, input data consists of one or more error reports that have to be represented by a vector in order to be processed by a classification algorithm. A straightforward solution would be to use the error type of the first event in a sequence as value of the first input vector component, the second type as second component, and so on. However, it turns out that such a solution does not work: If the sequence is only shifted one step, the sequence vector is orthogonally rotated in the input space and most classifiers will not judge the two vectors as similar. One solution to this problem has been proposed by Domeniconi et al. [2002]: SVD-SVM (Singular-Value-Decomposition and Support-Vector-Machine) borrows a technique known from information retrieval: the so-called “vector space model” representation of texts [Manning and Schütze 1999, Page 539]. In the vector space model representation, there is a dimension for each word of the language. Each text is a point in this high-dimensional space where the magnitude along each dimension is defined by the number of occurrences of the specific word in the text. SVD-SVM applies the same technique to represent error event sequences: Each dimension of the vector corresponds to one event type and the magnitude is either a boolean value indicating whether an error type is present or not, the number of occurrences of the event type in the data window, or a binary encoded timestamp. SVD-SVM performs two steps: The first step involves simplification and de-correlation of event sequences by use of singular value decomposition. The second step involves classification by use of support vector machines. The approach has been applied to data of a production computer network where failures were defined to be the occurrence of an error event with severity level “critical” or “fatal”. Further details on this method can be found in Appendix K.

6. SUMMARY AND CONCLUSIONS

We have surveyed failure prediction methods that have been proposed and many of them used to predict failures of computer systems online. The goal of online failure prediction is to identify if a failure, that is a misbehavior of the system resulting

in deviation from expected output, will occur in the near future. This can be accomplished by runtime observation and measurement of the current system state. Although failure prediction approaches exist that base predictions on upcoming failures without measuring the current system state (e.g., by lifetime probability distributions), these are beyond the scope of this survey.

We have developed a comprehensive taxonomy in order to structure and classify a wide spectrum of existing techniques dealing with online failure prediction to help potential users to easily find a method that might be attractive in their application environment. Online failure prediction methods can be divided into four categories according to the type of input data that is processed. Specifically, the approaches evaluate: (a) the times of previous failure occurrence (failure tracking), (b) monitoring data reflecting symptoms (side-effects) of errors, (c) the detection of errors that have not yet evolved to become a failure, or (d) search for undetected errors by means of auditing. Three of the categories have been divided further by the principle approach and subsequently by the methods that are used. Concepts have been briefly explained, followed by appropriate references.

We have surveyed almost 50 approaches from various research areas such as pattern recognition, control theory and function approximation. The majority of approaches described focus on failure prediction concerning software but there are also many methods predicting failures of hardware, e.g., [Hughes et al. 2002; Hamerly and Elkan 2001; Murray et al. 2003] or [Weiss 1999].

A comprehensive summary of all models/approaches together with demonstrated applications including appropriate references and classification can be found in Table III. In addition the table provides a brief synopsis of the approach and potential application areas and remarks. In order to shorten the table, the following numbers are used for text that appears several times across the table:

- ① failure-based long term prediction
- ② failure prediction in distributed systems
- ③ prediction of resource-scarcity failures
- ④ prediction of service level failures
- ⑤ single request failure prediction
- ⑥ component failure prediction
- ⑦ event-based failure prediction (as a superset to error reports)

Table III. Overview of all failure prediction techniques surveyed.

Category / Reference	Model / Approach	Area of Application	Potential Applications/ Remarks
1.1.1 Csenki [1990]	Jelinski-Moranda model improved by observed inter-failure times	Software reliability prediction	① Based on software quality
1.1.2 Pfefferman and Cernuschi-Frias [2002]	Failures modeled as non-stationary Bernoulli process	Software failures	① Adapts to changing system dynamics

Category / Reference	Model / Approach	Area of Application	Potential Applications/ Remarks
1.2 Liang et al. [2006]	Temporal / spatial compression of failures	Extreme-scale parallel systems	② Focus on long-running applications
2.1.1 Vaidyanathan and Trivedi [1999]	Semi-Markov reward model to predict resource consumption	Memory consumption in UNIX system	③, ④ Focus on workload
2.1.1 Li et al. [2002]	ARX model for resource utilization using additional system variables as input	Prediction of Apache webserver resource exhaustion	③, ④ Accounts for stationary and non-stationary effects
2.1.2 Andrzejak and Silva [2007]	Use of deterministic functions to approx. aging indicators as a function of workload metrics	Performance of Apache Axis SOAP server	③ Focus on workload-based input data
2.1.3 Hoffmann [2006]	Approximation of interval call availability by universal basis functions	Performance failures of a telecommunication system	③, ④ Also applied to response time and memory prediction in Apache webserver [Hoffmann et al. 2007]
2.1.3 Kapadia et al. [1999]	Approximation of resource usage by averaging values of similar points in the training data	Resource consumption (e.g., CPU time) of programs based on invocation parameters	③, ④ Is not regarding interference with other programs
2.1.3 / 1.2 Fu and Xu [2007]	Estimation of number of failures from CPU utilization and temporal and spatial correlation by use of neural networks	Failures of Wayne State University computing grid	②, ④ Focus on number of failures
2.1.3 Abraham and Grosan [2005]	Genetically generating code to approximate failure probability as a function of external stressors (e.g. temperature)	Power circuit failures of an electronic device	Applicable to systems where the root cause of failures can be assigned to a small set of stressors
2.2.1 Hamerly and Elkan [2001]	Naïve Bayes classification of SMART values	Hard disk failures	Based on independence assumption of monitoring variables. \Rightarrow variable selection or decorrelation required
2.2.1 Pizza et al. [1998]	Bayes-optimal discrimination between permanent and transient faults	Simulated component diagnosis	④ Failure prediction where short outages do not matter while permanent outages lead to a failure

Category / Reference	Model / Approach	Area of Application	Potential Applications/ Remarks
2.2.2 Turnbull and Alldrin [2003]	Radial basis function network to classify a sequence of monitoring values	Motherboard failure prediction based on temperature and voltage	③, ④ Results refer to data set with equally likely failures and non-failures
2.2.2 Berenji et al. [2003]	RBF rule base obtained by clustering from simulated training data	Hybrid combustion facility	Operates on continuous input and output of components
2.2.2 Murray et al. [2003]	Support Vector Machine classification of SMART values	Hard disk failures	Achieves better recall but at the cost of higher false positive rate than [Hughes et al. 2002]
2.2.2 Bodík et al. [2005]	Naïve Bayes classifier applied to hit frequencies of most frequently used web pages	Detection of non fail-stop failures in a large Internet application	②, ④ Focus on access statistics
2.2.3 Kiciman and Fox [2005]	Decision tree to classify whether requests are successful or not from recorded runtime paths	Identify faulty components in J2EE application server	⑤ Based on runtime properties such as component IDs used, etc.
2.2.3 Daidone et al. [2006]	Use of HMMs to infer true state of components from sequences of component probing results	Identify whether a component is faulty (simulations)	⑥ Based on unreliable probing
2.3.1 Elbaum et al. [2003]	Detection of unknown sequences of functional events such as function calls, etc.	Failures of email client “pine”	⑤ Single-threaded applications
2.3.1 Hughes et al. [2002]	Statistical rank sum test of monitored values in comparison to stored fault-free samples of SMART values	Failures of hard disk drives	Monitoring variables must relate closely to failures, little computational overhead
2.3.1 Chen et al. [2002]	Pinpoint: Identification of failure correlated components by clustering of runtime paths	Failed components of a J2EE application	④, ⑤ Applicable if requests traverse many components
2.3.1 Bodík et al. [2005]	χ^2 test-based comparison of hit frequencies of web pages to a “historically normal” distribution	Prediction of non fail-stop failures of major Internet site	②, ④ Failure prediction based on usage statistics, applicable if significant number of usage counts is available

Category / Reference	Model / Approach	Area of Application	Potential Applications/ Remarks
2.3.2 Murray et al. [2003]	Unsupervised clustering in order to determine areas of SMART values where the disk operates normally	Failures of hard disk drives	④ Number of clusters needs to be specified
2.3.3 Ward et al. [1998]	Comparison of current measurement to normal distribution using a statistical test	TCP connections of proxy servers	③, ④ Works for failures indicated by a single variable, assumption of stationary process
2.3.3 Chen et al. [2004]	Probability of runtime paths computed using PCFGs	Request failure detection in J2EE appl. server, Tellme enterprise voice appl. network, and eBay online auction system	④, ⑤ Component-based systems
2.3.4 Kiciman and Fox [2005]	Comparison of component interactions to reference “peer model” using χ^2 test	Detect anomalous component instances in J2EE application server	⑥ Densely connected component interaction graph required
2.3.5 Singer et al. [1997]	Estimated state computed by MSET is compared to the measured state by sequential probability ratio test	Detection whether a memory consuming fault injector is active or not, and detection of software aging in transaction processing servers	④ Focus on correlated multivariate system variables, details not publicly available due to patent restrictions
2.4.1 Garg et al. [1998]	Smoothing of monitored resources, seasonal Kendall test, trend estimation	Memory, file table size, process table size in UNIX system	③ Works for systems where time-based (rather than workload-based) approach is appropriate
2.4.1 Castelli et al. [2001]	Fitting of several curve types, selecting the best, extrapolation until resource exhaustion	IBM xSeries Software Rejuvenation Agent	③ Li et al. [2002] showed inferior performance compared to ARX modeling
2.4.1 Cheng et al. [2005]	Fuzzy logic to detect “unhealthy state”, linear regression to determine mean time to resource exhaustion	High availability cluster system	③ sufficiently linear resource evolution required
2.4.2 Shere-shevsky et al. [2003]	Detection of software aging by use of the Hölder exponent and subsequent Shewhart change detection algorithm	Predict system crashes of Windows NT 4.0 and Windows 2000 servers	Prediction of any software aging-related failures

Category / Reference	Model / Approach	Area of Application	Potential Applications/ Remarks
2.4.3 Hellerstein et al. [1999]	Application of several time series models to remove stationary and non-stationary effects, predict failure by threshold violation	Predict number of HTTP operations on production server	③ Requires sufficient amount of data in order to identify stationary / non-stationary effects
2.4.3 Vilalta et al. [2002]	Stochastic time series model accounting for time-of-the-day, weekly, and monthly effects, generalized likelihood ratio test for change-point detection	Forecasting webserver workload by predicting the number of HTTP operations per second	③ Requires sufficient amount of data in order to identify stationary / non-stationary effects
2.4.3 Sahoo et al. [2003]	Various linear time series models including ARMA to predict e.g., percentage of system utilization, idle time, network IO	350-node cluster	②, ③
2.4.3 Meng et al. [2007]	Rough set wavelet network to predict next monitoring value	Memory consumption of J2EE server	③ One step ahead prediction ⇒ lead-time equal to monitoring interval
2.4.3 Ning et al. [2006]	Fuzzy wavelet network to predict next monitoring value	Memory consumption of J2EE server	Similar to [Meng et al. 2007]
3.1 Hätönen et al. [1996]	Episode rules determined by data mining followed by manual selection of rules	Telecommunication Alarm Sequence Analyzer (TASA)	⑦ Profound system knowledge required, not suitable for dynamic systems due to manual rule selection
3.1 Weiss [1999]	Timeweaver: rule base generation from scratch using genetic programming	Telecommunication equipment failure data	⑦ Events must contain several attributes, limited expressiveness in terms of temporal properties
3.1 Vilalta and Ma [2002]	Extraction of event sets that indicate an upcoming failure by data mining	Failure prediction in a 350-node cluster system	⑦ Focus on class imbalance
3.2 Nassar and Andrews [1985]	Detection of changes / trends in distribution of error types	event log data of three DEC computing systems	⑦ Estimation of distributions requires long time windows ⇒ useful for slowly developing failures

Category / Reference	Model / Approach	Area of Application	Potential Applications/ Remarks
3.2 Lin and Siewiorek [1990]	DFT: Heuristic rules investigating time of error occurrence	Error log of distributed machines running the Andrew file system at Carnegie Mellon University	② ⑦ Builds on system components, heuristic rules need to be adapted
3.2 Lal and Choi [1998]	Aggregation of errors and trend detection in the frequency of occurrence	Errors and failures in a UNIX server	⑦ Very simple method with little computational overhead
3.2 Leangsuk-sun et al. [2004]	Thresholds on sensor measurements generate events. Predict a failure if frequency of aggregated events exceeds threshold	High availability, high performance Linux cluster	Simple heuristic method, no results presented
3.3 Salfner et al. [2006]	SEP: error report sequences modelled using a semi Markov model	Performance failures of a telecommunication system	⑦ Includes both type and time of error reports
3.3 Salfner and Malek [2007]	Model error report sequences using hidden semi-Markov models (HSMM)	Performance failures of a telecommunication system	⑦ Includes both type and time of error reports, can handle permutations in event sequences
3.4 Levy and Chillarege [2003]	Detection of changes in subsystem order built from their error generation frequency	Comverse Voice Mail system	②, ④, ⑥ Significant amount of errors without successive failures needed for reliable estimation of component order
3.5 Domeniconi et al. [2002]	SVD-SVM: Using techniques from natural language processing, classify error sequences using support vector machines	Production computer network with 750 hosts	⑦

In order to provide better insight into categories, appendices describe various approaches that are representative for each category. Table IV in Appendix A lists the approaches that are described in Appendices B to K. “Classification” refers to the category of our taxonomy the approach is assigned to, “application area” denotes the areas the method was or could be implemented in, the metrics which were used to assess the quality of the corresponding failure prediction approach are listed in “metrics” and, finally, “failure model” names the failures and/or faults that can be predicted by the examined technique. Most of these techniques have been tested and evaluated in practice.

Let us reiterate and summarize: dependability and resilience are and will remain a permanent challenge due to:

- Ever-increasing systems complexity
- Ever-growing number of attacks and threats
- Novice users
- Third-party, open-source software, Commercial-Of-The-Shelf (COTS) components
- Growing connectivity and interoperability
- Dynamicity (frequent configurations, reconfigurations, updates, upgrades and patches, ad hoc extensions)
- Systems proliferation to applications in all domains of human activity

In such circumstances proactive fault management by runtime monitoring and online failure prediction seem to be one of a very few alternatives for effective online dependability assessment and enhancement. In our opinion, proactive fault management (where failure prediction plays a crucial role) is the key enabler for the next generation of dependability improvement. Researchers have adopted various concepts from computer science resulting in a diverse landscape of approaches to online failure prediction. The goal of this survey is to provide an overview of existing approaches including key properties and fields of application in order to prepare researchers for the next challenge of proactive fault handling: the prediction-based triggering of effective countermeasures to enhance system availability by potentially an order of magnitude or more [Candea et al. 2004; Salfner et al. 2005] by using effective failure avoidance and downtime minimization methods.

Acknowledgment

We would like to express our gratitude to the reviewers who provided several constructive comments that helped to improve this survey.

APPENDIX

A. LIST OF PREDICTION METHODS DESCRIBED IN APPENDIX

Table IV. Overview of reference online failure prediction methods that are described in detail in Appendices B-K.

	Class	Application Area	Metrics	Failure Model
BlueGene/L [Liang et al. 2006]	1.2	extreme-scale parallel systems	recall	transient and permanent faults of software and hardware
Reward Model [Vaidyanathan and Trivedi 1999]	2.1.1	software rejuvenation	not specified	time of resource exhaustion
UBF [Hoffmann 2006]	2.1.3	large software systems	ROC, AUC, cost-based metric	permanent and transient faults
Naïve Bayes [Hamerly and Elkan 2001]	2.2.1	disk drives	true and false positive rate, ROC	disk drive failures
Threshold Violation [Vilalta et al. 2002]	2.4.3	systems management, workload forecasting	false positive rate	transient, intermittent and permanent faults
Timeweaver [Weiss 2002; 1999]	3.1	telecommunication systems, hardware	recall, precision, F-measure	intermittent and reoccurring faults
Eventset [Vilalta and Ma 2002]	3.1	computer networks, financial transactions	false positive and false negative rate	intermittent and permanent faults
DFT [Lin and Siewiorek 1990]	3.2	electromechanical, electronic devices	performance, frequency of rule firings	intermittent faults
HSMM [Salfner and Malek 2007]	3.3	large software systems	precision, recall, false positive rate, F-measure, ROC	permanent and intermittent faults
SVD-SVM [Domeniconi et al. 2002]	3.5	computer networks	error rates	critical and fatal error events

Please note that a direct comparison of the approaches with respect to certain metrics cannot be provided due to the diversity of experimental conditions as well as lack of details in the papers. Therefore, we opted for summarizing key results for each method independently. For more information, the interested reader might refer to the original publication.

B. BLUEGENE/L FAILURE PREDICTION

Authors, developed at: Yinglung Liang, Yanyong Zhang, Rutgers University, New Jersey, USA; Morris Jette, Lawrence Livermore National Laboratory, California, USA; Anand Sivasubramaniam, Penn State University, Pennsylvania, USA; Ramendra Sahoo, IBM T. J. Watson Research Center, New York, USA

Classification: 1.2

Special application areas: Failure prediction on extreme-scale parallel systems such as IBM BlueGene/L.

Basic idea: The authors use event logs containing reliability, availability and serviceability data from IBM's BlueGene/L to predict memory, network and application I/O failures of the supercomputer. They develop three prediction algorithms based on failure occurrence before non-fatal events and the spatial skewness of failure occurrence. A three-step filtering algorithm is applied to extract and categorize failure events as well as to perform temporal and spatial compression. Failure prediction is based upon temporal and spatial failure characteristics and correlations between fatal and non-fatal events.

Outline of algorithm:

- (1) After applying the filtering algorithm, failure events that are reported by the same job are clustered. Events that are detected by different jobs are not merged.
 - (a) Events with severity either fatal or failure are extracted. Failures are further classified into categories according to the subsystem in which they occur: memory, network, application I/O, midplane switch and node card failures.
 - (b) Failure events that occur within the same subsystem and are reported by the same location as well as the same job are combined into a cluster if the interarrival time between these events is lower than some pre-specified threshold (e.g., five minutes). This step is called temporal compression.
 - (c) As failures can be reported by multiple locations, spatial filtering removes all failure events from different locations that are reported by the same job and contain the same event description, within a certain time window (e.g., five minutes).
- (2) Prediction based on inter-event times: After the occurrence of a network or application I/O failure more failures are likely to occur shortly.
- (3) Prediction based on spatial skewness: If some components have reported more failure events than others, it is likely that more failures will follow in the near future at the same location. This is especially true for network failures.
- (4) It has been observed that large bursts of non-fatal events are mostly followed by fatal failure events. If a job has experienced two or more non-fatal events, it is likely that either itself or the following four jobs may be terminated because of a fatal failure.

Metrics used: The quality of the failure prediction methods are assessed using recall.

Input data used: RAS (reliability, availability and serviceability) event logs from IBM's BlueGene/L supercomputer serve as event-driven input dataset. In two and a half months 1.318.137 events occurring in various system components have been recorded.

Failure models: The authors intend to predict transient and permanent failures of hardware and software as well.

Results, application areas, experiments: The prediction methods were applied to BlueGene/L, a supercomputer with 128K processors. 37% of all network failures and 48% of all application I/O failures were predicted by using temporal compression. If network and application I/O failure events were merged, 370 out of 687 failures (54%) were predicted. By monitoring the following five jobs after the occurrence of a non-fatal event, 82% of the total fatal failures can be predicted. Furthermore, if five jobs after observing a fatal failure are checked, 9.5% additional fatal failures can be caught.

Main reference: [Liang et al. 2006]

C. SEMI-MARKOV REWARD MODEL

Authors, developed at: Kalyanaraman Vaidyanathan, Kishor S. Trivedi, Duke University, North Carolina, USA

Classification: 2.1.1

Special application areas: Software Rejuvenation.

Basic idea: The authors present a semi-Markov reward model that is based on workload and resource usage data to allow the prediction of resource exhaustion due to software aging. Thus software rejuvenation processes may be controlled. A semi-Markov process utilizing sojourn time, i.e., the time spent in a state, and transition probabilities is used as base model. In order to build a state-space model different workload states are identified by monitoring and clustering four system parameters. Corresponding to two system resources (used swap-space and free memory), a reward is assigned to each workload state based on the rate of resource consumption in this state. The model is solved to estimate the resource usage trend and to predict the time to exhaustion of resources.

Outline of algorithm:

- (1) To identify essential workload states, four system variables are taken into consideration: the number of process context switches, the number of system calls, the number of page-in operations and the number of page-out operations. Therefore, each data point in a four-dimensional space represents a workload measured at a particular time. These data points are clustered such that the sum of squares within each cluster is minimized.
- (2) A state-transition model is built by computing the transition probability p_{ij} from a state i to a state j for each workload state using the formula:

$$p_{ij} = \frac{\text{observed number of transitions from state } i \text{ to state } j}{\text{total observed number of transitions from state } i} \quad (10)$$

- (3) The distribution of sojourn time for each workload state is determined.
- (4) A reward rate, which is assigned to each workload state for each resource, is computed as the slope (rate of increase/decrease per unit time interval) of a specific resource in a specific workload state. This is done by using a non-parametric procedure by Sen [1968] that computes the slope as the median of the difference quotients of all pairs of measurement points x_i and x_j for which $i > j$.

Metrics used: The authors do not specify any metrics to assess the quality of their approach.

Input data used: Continuous parameters concerning the operating system resource usage and the system activity were periodically monitored on nine UNIX workstations over a period of three months. However, in the referenced paper, only data of one machine is used.

Failure models: It is assumed that the exhaustion of operating system resources, such as memory and swap-space, may lead to software failures. Therefore, a

measurement-based methodology is developed that takes the system workload into account to estimate a resource usage trend and to accomplish failure prediction, i.e., to predict the time of exhaustion of resources.

Results, application areas, experiments: The semi-Markov reward model was solved using the Symbolic Hierarchical Automated Reliability and Performance Evaluator (SHARPE) [Sahner et al. 1996]. The expected accumulated reward over time with respect to a specific resource is considered to be an estimator of the resource usage trend. It is shown that the developed model gives better trend estimates than a purely time-based approach. However, since interactions between resources are not taken into account, the estimated time of resource exhaustion does not necessarily coincide with a system failure.

Main reference: [Vaidyanathan and Trivedi 1999]

D. UNIVERSAL BASIS FUNCTIONS (UBF)

Authors, developed at: Günther A. Hoffmann, Humboldt University, Berlin, Germany

Classification: 2.1.3

Special application areas: High level modeling for software systems, single server scenarios.

Basic idea: Given a software system that permanently monitors characteristic variables such as workload, number of processes, used I/O bandwidth, the probability of failure occurrence is assumed to be a function of a selection of these input variables. This functional interrelation is learned from previously recorded measurements by proposing a machine learning approach: universal basis functions. UBF are a further development of radial basis functions (RBF) where each kernel is a weighed mixture of two kernels, e.g., a mixture of Gaussian and sigmoid.

Outline of algorithm: The approach is inspired by machine learning techniques. It employs offline selection of parameters (variable selection) from previously recorded training data and is then used to perform an online prediction of failures.

- (1) The probability of failure occurrence is modeled as a weighted mixture of universal basis functions:

$$f(\vec{x}) = \sum_{i=1}^N \alpha_i(\vec{x}) G_i(\vec{x}, \beta_i) \quad (11)$$

where α_i are weights and G_i are universal basis functions. More precisely, each universal basis function G_i is a mixture of two kernel functions ϕ_1 and ϕ_2 (such as sigmoid or Gaussian) weighed by β :

$$G_i(\vec{x}, \beta) = \beta \phi_1(\vec{x}, \vec{\lambda}_{1,i}) + (1 - \beta) \phi_2(\vec{x}, \vec{\lambda}_{2,i}) \quad (12)$$

where $\vec{\lambda}$ denotes the parameter vector of the kernel function (e.g., μ and σ in case of a Gaussian kernel).

- (2) The goal of training the model from previously recorded training data is to determine the model's parameters α_i , β_i , $\lambda_{1,i}$ and $\lambda_{2,i}$. This is achieved using an iterative evolutionary optimization algorithm that tries to find an optimal set of parameters such that the mean square error of the training dataset is minimized:

$$\Lambda = \operatorname{argmin}_{\Lambda} \sum_{j=1}^M (f(\vec{x}_j) - y_j)^2 \quad (13)$$

where Λ denotes the set of all model parameters and the tuple (x_j, y_j) is one data point in the training dataset. y_j is the target value of the function f : It equals 1 if a failure had occurred during measurement j and 0 if no failure occurred.

- (3) Once the model is trained, the measurements that are obtained during runtime are used to evaluate equation 11. The resulting value for f is an estimate of the

probability that a failure will occur. If it exceeds some predefined threshold, a failure warning is raised. It is a matter of fact that in most cases prediction performance is best if not all measurements that are available are fed into the model. Therefore, an indicative choice of input variables has to be selected carefully. In order to obtain such a selection, techniques known as “variable selection” have to be applied (see, e.g., Guyon and Elisseeff [2003] for an introduction).

Metrics used: Prediction quality has mainly been assessed using ROC plots and AUC. A cost-based metric that assigns cost to true positive and false positive predictions has been introduced in [Hoffmann et al. 2004] and improved in [Hoffmann 2006].

Input data used: Since the approach is based on measurements that reflect the effects of faults, it is focused on periodic measurements of continuous variables. However, event-driven data can additionally be included.

Failure models: The approach is based on the assumption that a functional relationship between input-variables and the probability of failure occurrence exists. Furthermore, it tries to infer this relationship from previous samples. This implies that the relationship must be causal and must have been observed (at least with some similarity) several times before. This assumption holds for both permanent and transient faults that lead to failures.

Results, application areas, experiments: Experiments have been carried out using periodic measurements of a commercial telecommunication platform. The data had been collected with the UNIX System Activity Reporter (SAR) and comprised 192 different periodic measurements ranging from the number of running processes to memory consumption. After applying a variable selection technique only two variables have been used: the number of semaphore operations per second and the amount of allocated kernel memory. The method achieved 0.9024 AUC for 5 min lead time.

Although the method was originally developed to predict the occurrence of failures in a large commercial telecommunication system [Hoffmann 2006], the method has also been successfully applied to the prediction of resource consumption in the Apache webserver [Hoffmann et al. 2006].

Main references: [Hoffmann 2004; 2006; Hoffmann and Malek 2006; Hoffmann et al. 2006]

E. NAÏVE BAYES CLASSIFIERS FOR FAILURE PREDICTION

Authors, developed at: Greg Hamerly, Charles Elkan, University of California, San Diego, USA

Classification: 2.2.1

Special application areas: Hard disk drive failure prediction.

Basic idea: The authors propose two Bayesian methods for the prediction of hard disk drive failures: an anomaly detection algorithm that utilizes a mixture of naïve Bayes submodels and a naïve Bayes classifier that is trained by a supervised learning method. The first method builds a probability model only for drives behaving normal. The Naïve-Bayes Model is trained by using Expectation-Maximization and is hence called NBEM. The second method is computing conditional probabilities for SMART values belonging to the failure or non-failure class. As the authors are only giving little information on the classifier, it will not be described here in further detail.

Outline of algorithm:

Constructing the anomaly detector:

- (1) The probabilistic model used here is a mixture of naïve Bayes submodels, which can be seen as clusters. The model takes a data point as input, which may be a summary of hard drive behavior for a certain time interval, and outputs a probability of failure occurrence:

$$P(x) = \sum_k P(x|k)P(k) \quad (14)$$

$P(k)$ is the prior probability of a submodel k , $P(x|k)$ is the probability that the data point x is generated by submodel k . As in naïve Bayes approaches it is assumed, that the attributes x_i of a data point x are conditionally independent, the joint probability can be computed as the product of single attribute probabilities:

$$P(x|k) = \prod_{i=1}^d P(x_i|k) \quad (15)$$

To allow for smooth probability estimates, the values of the attributes are placed in bins, which are internal values representing the true attribute values. This approach uses equal-width binning, where the data range is divided into intervals of the same size. Each interval is represented by a bin.

- (2) The model parameters are learned from the training data. After initializing the model by assigning data points randomly to submodels, the expectation-maximization (EM) training starts. EM works in rounds of E- and M-steps: the E-step determines the probability for each data point that each submodel is generating this point. During the M-step the parameters $P(x_i|k)$ and $P(k)$ are updated and the logarithm of the likelihood is maximized.
- (3) A probability threshold t is chosen either by hand or learned experimentally. If the probability of the data point is below this threshold, the data point is

classified as anomalous.

- (4) A failure warning is raised if any of the data points is either identified as anomalous or as failure (by the classifier).

Metrics used: The authors use true and false positive rate as well as ROC curves to evaluate the quality of their prediction methods.

Input data used: The approach uses time-driven SMART (self-monitoring and reporting technology) values of 1936 Quantum Inc. disk drives as data set. SMART attributes comprise for example spin-up time, power-on hours and counts for seek errors and CRC errors.

Failure models: The presented methods are capable of predicting hard disk drive failures based on SMART values, which are representing the internal conditions of disk drives.

Results, application areas, experiments: NBEM as well as the naïve Bayes classifier have been applied to the input data set. Using a decision threshold of 0.005, NBEM achieves a true positive rate of 0.33 while raising false warnings with a probability of 0.0036. The classifier is able to identify 56% of all failures while having a false positive rate of 0.0082 at a class threshold t of 0.001. Overall, the standard naïve Bayes classifier performs better than NBEM. Nevertheless, NBEM still outperforms industry standard methods and the approach proposed in [Hughes et al. 2002].

Main reference: [Hamerly and Elkan 2001]

F. PREDICTION OF THRESHOLD VIOLATIONS

Authors, developed at: Ricardo Vilalta, Chidanand V. Apte, Joseph L. Hellerstein, Sheng Ma, Sholom M. Weiss, IBM T. J. Watson Research Center, New York, USA

Classification: 2.4.3

Special application areas: Systems management, especially prediction of workload.

Basic idea: The paper presents three predictive algorithms: (1) long-term prediction of performance variables such as disk utilization, (2) short-term prediction of abnormal behavior (e.g., threshold violations) and (3) short-term prediction of system events such as router failures. As we are interested in time series prediction, only the second approach will further be explained here. The authors construct a statistical model of the time-varying behavior of a production webserver - its HTTP operations per second (httpops) are of special interest. After removing non-stationary components (i.e., mean, daily, weekly and monthly effects), the algorithm searches for residuals to identify abnormal behavior.

Outline of algorithm:

- (1) To build the stochastic model, the effect of the time of day is considered first. v_{jd} denotes the value of httpops for the j -th five-minute interval (i.e., the time-of-day value) and the d -th day in the collected data. v_{jd} is decomposed into three parts: the grand mean μ , the deviation from the mean α_j due to the time-of-day value and an error term ϵ_{jd} that captures daily variability. Therefore, the model incorporating mean and daily effects is:

$$v_{jd} = \mu + \alpha_j + \epsilon_{jd} \quad (16)$$

The time-of-day effects are removed and the residuals are searched for more patterns.

- (2) The weekly effect is incorporated into the model: β_w denotes the effect of the w -th day of the work week. This is also a deviation from μ .
- (3) After removing the weekly effects, the model is extended once more to consider monthly effects on the data represented by γ_m . The model is:

$$v_{jdwm} = \mu + \alpha_j + \beta_w + \gamma_m + \epsilon_{jdwm} \quad (17)$$

- (4) The authors assume that the time index t can be expressed as function of (j, d, w, m) . Therefore, a second-order autoregressive model is introduced that extends equation 17:

$$\epsilon_t = \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + u_t \quad (18)$$

θ_1 and θ_2 are model parameters, which are estimated from the data, and u_t are random variables, which are independent and identically distributed.

- (5) After removing time serial dependencies, a change-point detection algorithm is applied that detects anomalies (e.g., an increase in the mean or the variance). Here the GLR (Generalized Likelihood Ratio) algorithm is used. A reference

time window is used to test whether the parameters of a test time window differ significantly.

Metrics used: Only false alarms, i.e., false positive rate, are used to assess the quality of the forecasting method.

Input data used: Time-driven input data is obtained over a period of eight months from a production webserver of a large company. It was collected in intervals of five minutes. The authors analyze HTTP operations per second.

Failure models: The approach is designed to predict anomaly behavior and is used here for workload forecasting of a webserver. Transient as well as intermittent and permanent faults can be detected.

Results, application areas, experiments: The method was applied to the webserver data of a day for which no abnormal behavior is apparent. As normal load fluctuations were considered, the algorithm did not raise any false alarms. Furthermore, no anomalies were detected.

To our knowledge no more results on experiments were published.

Main reference: [Vilalta et al. 2002]

G. TIMEWEAVER

Authors, developed at: Gary M. Weiss, AT&T Labs, New Jersey, USA

Classification: 3.1

Special application areas: Telecommunication Systems, Hardware (4ESS switches).

Basic idea: Timeweaver is a data mining system that generates a set of rules used to predict telecommunication equipment failures from network alarm messages (i.e., error messages) generated by 4ESS switches that route the majority of the AT&T network traffic. The set of rules is created “from scratch” using a genetic programming approach: starting from an initial set of rules, new rules are created by crossing and mutations. Each rule set is assessed using a fitness function that takes into account prediction quality and diversity of the rule set.

Outline of algorithm:

- (1) The alarms of the 4ESS switches served as target dataset. All kinds of failure alarms are replaced with a common failure alarm and redundant alarms are removed.
- (2) Data mining:
 - (a) Patterns are encoded as follows: Patterns are sequences of pattern-events, where each pattern-event corresponds to an event in the dataset (i.e., an alarm). Pattern-events are of the form `<device-id, device-type, diag-code, severity>`. The feature values in pattern-events may take on a wildcard-value. There are ordering constraints between successive events in the pattern. A pattern duration is associated with each pattern. Patterns are described by a pattern language.
 - (b) Each pattern-event in the pattern matches an event in the sequence, the specified ordering constraints are obeyed and all events involved in the match occur within a time period corresponding to the pattern duration. The sample pattern `351:<id20, TMSP, ?, Major> * <id20, TMSP, ?, Major> * <id20, TMSP, ?, Minor>` is matched if within 351 seconds two major alarms, followed by a minor alarm, occur on the same device. The diagnostic code does not matter as indicated by the wildcard “?”. The “*” represents the *after* constraint and specifies the relative ordering of the pattern-events.
 - (c) Recall and precision are computed for each pattern. Proportional to their fitness pattern are selected for combining and mutation to generate new patterns.
- (3) The process is iterated to modify the used parameters monitoring and warning time.

Metrics used: Evaluation of timeweaver comprises recall and precision. The fitness of prediction patterns is computed using the F-measure.

Input data used: The alarms of the 4ESS switches collected over two weeks serve as event-driven target dataset. It consists of 148,886 alarms whereas each alarm is characterized by five variables: the time the alarm is generated, a unique identifier

for the device associated with the alarm, the type of device, the diagnostic code of the alarm, and the severity of the alarm.

Failure models: The author intends to identify intermittent and reoccurring faults of the 4ESS switches.

Results, application areas, experiments: The target dataset was split into disjoint training and test sets. Timeweaver was applied to the training set and the discovered patterns were evaluated on the test set. While holding the monitoring time constant at eight hours, the warning time was varied and precision/recall curves were generated by ordering the patterns from most to least precise.

It is shown, that the precision of the prediction decreases as the recall increases. The performance of the rules depends heavily on the lead-time Δt_l (see Figure 4): the shorter the lead-time, the better the prediction.

Main references: [Weiss 2002; 1999]

H. EVENTSET METHOD

Authors, developed at: Ricardo Vilalta, University of Houston, Texas, USA; Sheng Ma, IBM T. J. Watson Research Center, New York, USA

Classification: 3.1

Special application areas: Computer Networks, Financial Transactions.

Basic idea: This data mining approach intends to predict errors, called target events, such as attacks in computer networks or illegal financial transactions, by capturing patterns that characterize the conditions preceding each target event. Such patterns are sets of event types and referenced here as “eventsets”. The algorithm performs several steps to find eventsets, which occur frequently before target events but not outside the time windows preliminary to failures (see Figure 16). After the validation of eventsets, eventsets that are overly general are filtered out and a rule-based system for failure prediction can be built.

Outline of algorithm:

- (1) First of all a target event is defined.
- (2) To find all frequent eventsets the following is done: All events occurring within a certain time window are maintained in memory. All event types within the window are saved as a new transaction on every occurrence of a target event. After analyzing all events, eventsets that are above a minimum support (i.e., that occur with a minimum probability before a target event) can be found.
- (3) After identifying frequent eventsets, eventsets that are frequent and accurate have to be found. Therefore, eventsets that are below a minimum degree of confidence (i.e., that occur with a minimum probability solely before target events and are rarely preceding non-target events) are filtered out. This is done by analyzing the number of times each of the frequent eventsets occurs outside the windows preceding target events.
- (4) The eventsets are validated: As the probability of an eventset occurring before a target event has to be higher than the probability of the eventset not preceding target events, any negative correlation between an eventset and the occurrence of target events are discarded.
- (5) A rule-based model that can be used for failure prediction is built. All eventsets are sorted according to their ranks, which depend on the degree of support and confidence. Eventsets that are too general are removed. The rule-based system predicts failures, if an eventset (i.e., rule) occurs within the current time window.

Metrics used: Prediction quality has mainly been assessed using the false positive and false negative rate.

Input data used: Both, a data generator and a production computer network serve as event-driven data sources.

Failure models: The authors intend to predict rare events, i.e., target events. Only reoccurring failures which were present in the training data can be predicted.

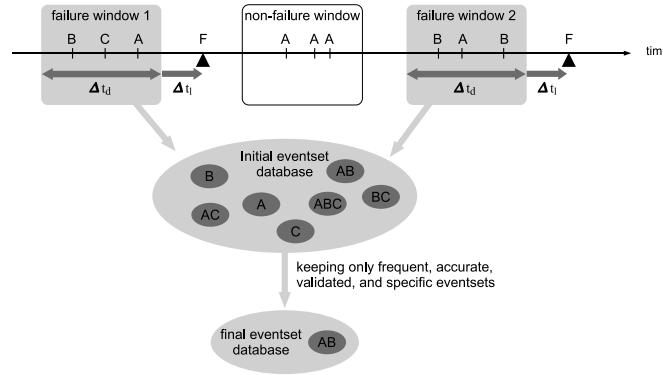


Fig. 16. Eventset Method.

This is true for intermittent as well as permanent faults.

Results, application areas, experiments: The method was first applied to artificial domains. A data generator created sequences of events, which were uniformly distributed over a time interval of one week. The first half of events served for training and the other half served for testing. Results show that patterns are easier to identify as the pattern size increases, as the number of event types increases and as the density of events decreases. Furthermore, the relationship between the level of minimum support and the amount of CPU time is illustrated.

The method was then implemented in a production computer network with 750 hosts. Over 26.000 events with 165 different types of events were collected during one month of monitoring. The analysis covered two critical types of target events: end-to-end response times to a host and URL time-outs. The results show that the size of the time window and the existence of eventsets frequently occurring before target events are crucial to the effectiveness of the method.

Main reference: [Vilalta and Ma 2002]

I. DISPERSION FRAME TECHNIQUE (DFT)

Authors, developed at: Ting-Ting Y. Lin, University of California, California, USA; Daniel P. Siewiorek, Carnegie Mellon University, Pennsylvania, USA

Classification: 3.3

Special application areas: Electromechanical and Electronic Devices.

Basic idea: The dispersion frame technique utilizes error logs for fault diagnosis and failure prediction working under the assumption that errors are manifestations of faults. A trend analysis is performed by determining the frequency of error occurrences whereas intermittent errors are extracted from transient errors in the system error log. The DFT applies two metrics: the dispersion frame (DF) is the interarrival time between successive error events of the same error type, the error dispersion index (EDI) is the number of error occurrences in half of a DF. A high EDI therefore exhibits a group of highly related errors. In order to predict failures a set of heuristic rules is defined that evaluate the number of error occurrences in successive DFs, which may result in a failure. Some of the rules test if errors occur in a distribution that is typical for upcoming failures (Weibull distribution), others are based on empirical experiences. Whereas the latter criteria are hardly useful for general problems, the usefulness of the first rules depends on whether the errors really fit the assumed distribution.

Outline of algorithm:

- (1) A time line of the five recent error occurrences for each observed device is drawn. Figure 17 shows the error events $i-4$, $i-3$, $i-2$, $i-1$, and i .
- (2) The previous DFs are centered around each error occurrence on the time line. For example, frame $i-3$, which is the interarrival time between events $i-4$ and $i-2$, is centered around events $i-3$ and $i-2$.
- (3) The number of errors from the center to the right end of each frame is designated as the EDI.
- (4) A failure warning is issued under the following conditions:
 - (a) *3.3 rule*: when two consecutive EDIs from the same frame are greater or equal to 3,
 - (b) *2.2 rule*: when two consecutive EDIs from two successive frames are greater or equal to 2,
 - (c) *2-in-1 rule*: when a DF is less than one hour,
 - (d) *4-in-1 rule*: when four error events occur within a 24-hour-frame,
 - (e) *4 decreasing rule*: when there are four monotonically decreasing frames and at least one frame is half the size of its previous DF.
- (5) Usually several iterations between steps 2 to 4 are performed before a warning is issued.

Metrics used: Evaluation of the DFT comprises the frequency of rule firings for each device and the performance of the prediction rules on each device.

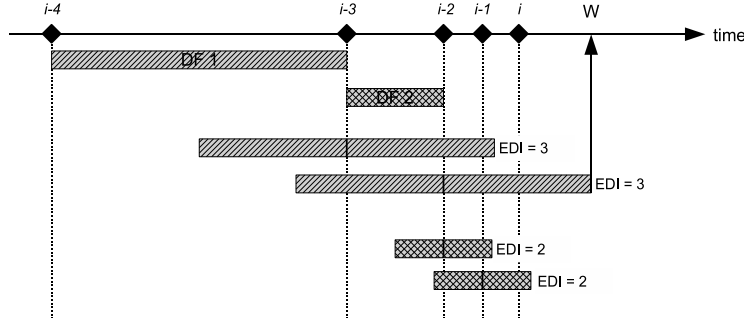


Fig. 17. Dispersion Frame Technique.

Input data used: Data was collected over a 22 month period from 13 VICE file servers of the campus-wide Andrew file system at Carnegie Mellon University. Event-driven data sources include the automatic error logs of the file servers and an operator's log.

Failure models: The authors assume that there exists a period of increasing intermittent error rate before most hardware failures. They are therefore extracting intermittent errors from the error logs to predict hardware failures.

Results, application areas, experiments: The DFT was implemented in a large-scale distributed computing environment at Carnegie Mellon University, which consists of workstations, high bandwidth networks and 13 file servers in a time-sharing file system called VICE. Over a period of 22 month there were 20 workstation-years of data collected.

The DFT requires only between three and five events in order to identify a trend to predict failures, that is only 20% of the error log entries required by statistical methods. 16 of 29 hardware failures that require repairs have been recorded by the online monitoring system, 15 of this 16 failures were correctly predicted while five false warnings were raised. The DFT for this case study therefore achieves recall of 93,75% and precision of 75%.

Main reference: [Lin and Siewiorek 1990]

J. HSMM-BASED FAILURE PREDICTION

Authors, developed at: Felix Salfner, Humboldt University, Berlin, Germany

Classification: 3.2

Special application areas: The approach aims at predicting of failures in large software systems.

Basic idea:

The approach is based on the assumption that failure-prone system behavior can be identified by characteristic patterns of errors. The rationale for this assumption is that due to dependencies within the software, a detected fault (error) in one system component leads —under certain conditions— to errors of dependent components. The goal is to identify and recognize those patterns that indicate an upcoming failure by Hidden Semi-Markov Models (HSMMs).

Two HSMMs are trained from previously recorded log data: One for failure and one for non-failure sequences. Online failure prediction is then accomplished by computing likelihood of the observed error sequence for both models and by applying Bayes decision theory to classify the sequence (and hence the current system status) as failure-prone or not (see Figure 18).

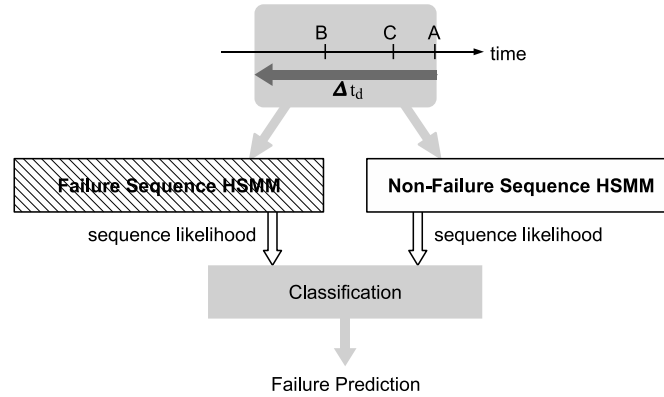


Fig. 18. Online failure prediction using hidden semi-Markov models.

Outline of algorithm:

- (1) A sequence of error messages can be interpreted as a temporal sequence. Training data is analyzed in order to extract error sequences preceding a failure by a certain lead-time (failure sequences) and not preceding any failure (non-failure sequences).
- (2) Two HSMMs are trained: One from failure and one from non-failure sequences. HSMMs extend standard hidden Markov models by defining cumulative probability distributions in order to specify the duration of state transitions. By

this approach, the two HSMMs learn to identify the specifics of failure and non-failure sequences.

- (3) After training, the model is used for online failure prediction: During runtime, each time an error occurs, the sequence \mathbf{o} of errors and delays that have occurred within some time window before present time are classified whether they belong to a failure-prone pattern or not. Classification consists of the following steps:
- (a) Sequence likelihood of \mathbf{o} is computed for both HSMM models:

$$P(\mathbf{o}|\lambda) = \sum_{\mathbf{s}} \pi_{s_0} b_{s_0}(o_0) \prod_{k=1}^L P(S_k = s_k, d_k = t_k - t_{k-1} | S_{k-1} = s_{k-1}) b_{s_k}(o_k) \quad (19)$$

where λ denotes HSMM parameters, $\mathbf{s} = [s_k]$ denotes a sequence of states s_k of length $L+1$ and t_k 's are the timestamps of the errors in the sequence, π_i 's denote initial state probabilities, and $b_i(o_k)$ denotes observation probability of state s_i for the k -th error observed in the sequence. The sum over \mathbf{s} indicates that all possible state sequences are investigated. The forward algorithm (c.f., [Rabiner 1989]) is used to compute Equation 19 efficiently. Sequence likelihood can be interpreted as a probabilistic measure of similarity of a sequence \mathbf{o} to failure and non-failure sequences.

- (b) Using Bayes decision theory, sequence \mathbf{o} is classified as failure-prone, iff

$$\log [P(\mathbf{o} | \lambda_F)] - \log [P(\mathbf{o} | \lambda_{\bar{F}})] > \underbrace{\log \left[\frac{c_{\bar{F}F} - c_{\bar{F}\bar{F}}}{c_{F\bar{F}} - c_{FF}} \right]}_{\in (-\infty; \infty)} + \underbrace{\log \left[\frac{P(\bar{F})}{P(F)} \right]}_{const.} \quad (20)$$

where c_{ta} denotes the associated cost for assigning a sequence of type t to class a , e.g., $c_{F\bar{F}}$ denotes cost for falsely classifying a failure-prone sequence as failure-free. $P(F)$ and $P(\bar{F})$ denote class probabilities of failure and non-failure sequences, respectively.

Metrics used: Prediction quality is assessed by using precision, recall, false positive rate, F-measure, and ROC plots.

Input data used: The approach analyses error messages of large systems which are at least determined by a timestamp and a discrete message type.

Failure models: The approach is data-driven, which means that HSMM failure predictors generalize from system behavior as observed in training data. For this reason, only reoccurring failures present in the training data can be predicted. This holds for permanent as well as intermittent faults.

Results, application areas, experiments: Analyses show excellent prediction performance on field data of an industrial telecommunication system. For the maximum F-measure, a precision of 0.85, recall of 0.66, and false positive rate of 0.0145 has been achieved.

Main references: [Salfner and Malek 2007; Salfner 2008]

K. SINGULAR VALUE DECOMPOSITION AND SUPPORT VECTOR MACHINES (SVD-SVM)

Authors, developed at: Carlotta Domeniconi, University of California, California, USA; Chang-Shing Perng, Ricardo Vilalta, Sheng Ma, IBM T. J. Watson Research Center, New York, USA

Classification: 3.5

Special application areas: Error event prediction in computer networks.

Basic idea: The approach describes the application of latent semantic indexing [Deerwester et al. 1990], an information retrieval technique, to error event prediction. Event sequences, where each event is characterized by a timestamp, the event type and the severity level, are obtained from continuous monitoring of a computer network. Each event type is represented by a dimension and each error event sequence that is observed within a certain time interval (i.e., the monitor window) is a vector in this high-dimensional space. The components of such a vector could encode the number of occurrences of the corresponding event type within the monitor window or their values could be a function of the event timestamps. Singular value decomposition is used to de-correlate event sequences and to reduce the feature space, whereas classification is performed by use of support vector machines.

Outline of algorithm:

- (1) Feature construction:
 - (a) Training sets of positive and negative examples for each target event are generated by monitoring the event history of time intervals preceding and far from the occurrence of a target event.
 - (b) Event sequences are mapped into vectors which are in turn represented as matrix D , whose rows are indexed by event types and the columns by training vectors. D has $m \times n$ dimensions: m different event types and n monitor windows.
- (2) Feature Selection:
 - (a) D is decomposed into $D = U\Sigma V^t$ by performing the SVD. U and V are square orthogonal matrices. Σ has the same dimensions as D , but is only non-zero on the diagonal. It contains the singular values with $\bar{\sigma}$ as their average value.
 - (b) k is set to the number of singular values which are above $\bar{\sigma}$.
 - (c) To reduce the dimension of the feature space, the vectors are projected into the subspace spanned by the k largest singular values. Therefore, the projection operator $P = U_k^t$ is constructed. U_k consists of the first k columns of U . By computing $\hat{l}_i = (Pl_i) \in \mathbb{R}^k$ the vectors l_i are projected into the selected k dimensions and a new training set is obtained.
- (3) A support vector machine is trained for classification and prediction using the training set of the step before.

Metrics used: Evaluation of SVD-SVM comprises error rates.

Input data used: The system management event messages of a computer network with 750 hosts are used as event-driven dataset. Within 30 days 26.554 events are collected with 692 events rated critical and 16 fatal. 164 event types were identified.

Failure models: The authors focus on system management events and intend to predict error events with severity either critical or fatal (i.e., target events).

Results, application areas, experiments: The approach was applied to the data of a production computer network. Two critical event types were predicted: “CRT_URL_Timeout”, which indicates that a website is not accessible, and “OV_Node_Down”, which indicates that a managed node is down.

Various experiments have been carried out to compare different feature construction processes: the event types were encoded by existence, by the number of their occurrence and by the times of their occurrence. The best performance has been obtained with existence as feature construction process. Furthermore, an experiment has been performed to determine the proper length of the monitor window. The authors discovered that the error rate, the number of selected dimensions and the window length correlate: the number of selected dimensions grows as the length of the monitor window increases. A stable point is reached when the error rate comes to its minimum.

Results of offline and online prediction are compared to C4.5 [Quinlan 1993], a standard machine learning algorithm, and SVM. SVD-SVM and SVM mostly show a similar performance, whereas C4.5 is in most cases the worst performer. The error rates of SVD-SVM range from 6.8 to 7.7 for offline, and 7.2 to 8.6 for online prediction.

Main reference: [Domeniconi et al. 2002]

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