Automated Fingerprint Identification: An Independent Study

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AUTOMATED FINGERPRINT IDENTIFICATION:

AN INDEPENDENT STUDY

by

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1. Introduction

We want to state that we consider it a privilege to have been asked to conduct this independent study for the FBI. Also, we wish to thank the many individuals who went to great efforts to provide us with the necessary background information.

The purpose of this report is to provide findings of our Independent Study of Automated Fingerprint Identification for the FBI. The emphasis of this study was to provide a "fresh look" at the entire fingerprint problem. The first steps included an analysis and an evaluation of existing and projected processes. However, the majority of the study was devoted to the determination of alternative or innovative approaches not currently under consideration.

This is a completely independent study and the opinions and conclusions are strictly our own. In fact, the majority of our information came from sources external to the Bureau. In the sections that follow we provide background, analysis, and conclusions.

1.1. Background

(a) The Identification systems for the FBI have evolved quite slowly over a number of years and do not meet the current requirements of the users. The FBI has a "revitalization and relocation" plan to replace and revise existing systems and to relocate all Identification Division (ID) staff systems, and operations from Washington D.C. to West Virginia. The technical component of this plan, which is the concern of our report, is the Integrated Automated Fingerprint Identification System, or "IAFIS" (an extension of the standard acronym for any automated fingerprint identification system or "AFIS").

(b) The major objectives of IAFIS include: providing identification services to user agencies, including state bureaus; supporting a paperless environment; and enabling the Identification Division to handle an ever increasing workload while maintaining staff size.

(c) As indicated above, the purpose of this study is to provide further insight into the potential risks inherent in moving ahead with the current plans for IAFIS. In particular, one might summarize a major focus of our efforts as an investigation into *fresh directions into searching and matching.*

One of our major goals was to ensure development of an optimal ID system which would not be rendered obsolete at the outset by existing or future technological developments. In addition, we hoped that our efforts would help the government optimize investments in these areas, avoiding potential financial and technical disasters.

1.2. Critical Issues for IAFIS

The critical issues we initially identified for consideration in the design of IAFIS are discussed below.

(a) REVITALIZATION:The revitalization effort appears to be the most vital issue facing the ID. In particular, one needs to answer major questions associated with the plan: What can new technology do for IAFIS? How can the FBI take advantage of these developments? Indeed, can or should the FBI take the lead itself in developing new and innovative methods in this field?

(b) AVOIDING FAILURE AND DISASTER: Reliability and cost also function as major issues when attempting to avoid a future technical failure and disaster. An evaluation of IAFIS must concentrate on the reliability and accuracy of the proposed plans. In addition, one must also consider the major costs that would be associated with an obsolete system.

(c) SPECIFIC PROBLEMS AND THEIR SEVERITY: A quick overview of IAFIS reveals some immediate problems. What are some of these problems and do they pose significant risks for IAFIS?

It appears that competition from state run AFISes has driven the recommendations and resulting structure for the FBI IAFIS. Thus, expectations seem to be that an IAFIS that will work at least as well as these state systems. However, in comparison with state run AFISes it is clear that scaling of computer power poses special problems for the large FBI database.

Also, barring major advances in automatic classification and verification, the present plans imply a need for special-purpose hardware. This hardware represents a major cost for IAFIS and is inherently risky if it turns out to be obsolete or totally unnecessary by the time it is implemented.

Another problem directly related to evaluating IAFIS and alternative methods is the availability of existing algorithms for classification and verification tasks. Indeed, it appears that there is no reliable method for automatic classification at this time. This observation receives more attention later in this report.

(d) CONSEQUENCES OF FAILURE: We feel that the FBI needs to recognize the possible consequences of proceeding with the proposed IAFIS. These consequences include possible loss of function (which, although unlikely, would be intolerable); excessive actual cost (fairly likely, and undesirable); and opportunity costs (almost assured with present plans, and barely tolerable).

1.3. Project Definition and Strategy

After our initial background study of IAFIS we have concluded:

(a) There are lots of new, highly relevant mathematical and computational advances which could make major contributions to the future effectiveness of IAFIS.

(b) Without further study, no one method can be immediately identified as a sure bet for 1994.

(c) We feel that the FBI needs to consider these methods as possible alternatives or enhancements.

(d) Finally, the FBI needs a strategy for pursuing new methods, beginning with the identification of the good, the bad and the uncertain possiblilities.

In the remainder of this report we reveal our strategies for identifying AFIS methods, our factual findings and our recommendations based on these findings.

We divided the research program for this study into internal and external sources. The internal program was devoted to the collection of necessary background information for IAFIS. This work was largely performed at FBI headquarters in Washington. However, as stated earlier, the majority of our findings came from sources external to the FBI. These sources included our own research and contacts as well as sources from prominent academic institutions, think tanks and government sponsored laboratories.

2. Methods

2.1. In-House Meetings and Interviews

We conducted an extensive series of meetings with various personnel involved with existing or projected tasks associated with IAFIS. These meetings included consultations with tech and latent examiners, in-depth interviews with R&D project managers, meetings with representatives from MITRE, the UK, and researchers associated with FBI funded projects at NIST.

We also examined existing computer and Automatic Fingerprint Reader System (AFRS) facilities, including a complete breakdown of the entire semi-automatic Ident process, both for tech and latent fingerprints. In conjunction with this background search we collected numerous research papers which we have combined together to form a research library of recent technological developments relevant to this study. Other in-house meetings included briefings on related topics such as Live-Scan fingerprints. Some of the same issues and problems associated with the latent process and live-scan also become issues in the IAFIS analysis. We address this in more detail in Section 3.4.4.

2.2. External Research Sources

(a) As indicated above, much of our research came from external sources, investigating current developments in mathematics, computer science, artificial intelligence and computer vision.

Both investigators presented papers at major conferences while conducting this study, summer 1991. These conferences were:

- The International Conference on Industrial and Applied Mathematics

- The International Joint Conference on Neural Networks

Both conferences provided us with numerous opportunities to gather information directly from experts in related fields from around the world. Many of these contacts lead to further collaborative investigations, some of which are listed below.

(b) A major goal of our study was to seek out new and innovative approaches to the fingerprint problem.

To this end we met with experts from a wide variety of academic, industrial and governmental institutions. Some of these institutions included the Johns Hopkins Applied Physics Laboratory (APL), ONR, Oxford University, the Jet Propulsion Laboratory (JPL), the National Center for Supercomputer Applications (NCSA) at the University of Illinois, the University of South Florida, the University of Maryland, George Mason University, the National Institute of Standards and Technology (NIST), University of Massachusetts Medical School, Yale University, the David Taylor Research Center, MITRE and other commercial fingerprint firms.

It should be noted that this segment of our investigation was also augmented by an extensive literature search of pertinent papers and journal articles. (These are papers not currently on file at the FBI.) We have also included these materials in our creation of an up-to-date research file for the FBI. Many of the most relevant papers in this file are cited in this report and listed in the References section.

2.3. Assimilation of Findings

(a) Both investigators met at Yale University to compare and combine respective findings. We jointly analyzed various options for IAFIS and agreed on a final set of conclusions and recommendations. We again want to emphasize that this was a completely independent effort.

(b) Our criteria for conclusions included issues of cost and associated risks inherent in the IAFIS plan. In particular, we addressed the potential risk of obsolescence and future technological development.

(c) In order to reduce major risks with IAFIS our analysis concluded that an appropriate avenue would be to diversify investments through a research program. In particular, we are recommending short, medium and long term investments.

2.4. Result: Risk and Diversification

(a) Our main conclusions revolved around the observation that conventional IAFIS (as currently proposed for 1994) is necessarily risky. Indeed, the alternative of devoting all efforts to a completely new research program is also inherently risky. But how can the FBI proceed while minimizing the risks of obsolescence and technological developments and still meet required development plans for the next two years?

(b) We believe that the answer lies in the term "DIVERSIFICATION". As with most financial plans, whether corporate, governmental or on a smaller scale, future success is often ensured through a "diversified investments". In this case (as in many financial situations), a useful form of diversification involves short, medium and long term investments.

So we are recommending that the FBI adopt a similar diversification venture, dividing efforts into three areas:

(1) conventional IAFIS with small modifications
(2) medium term research
(3) long term research

This strategy is illustrated schematically in figure 1, showing a "diversified portfolio" of AFIS investments. The idea is that if conventional IAFIS (which we will define in section 3) runs into trouble, the same facilities can be used to implement new and more capable AFIS methods resulting from an investment in medium or long-term research. Or, if the research fails, one can at least fall back on conventional IAFIS. It is well known among economists and financiers that a portfolio of independently risky investments is much less risky than any single component of the portfolio. Still, what happens if all of these inherently risky approaches run into trouble simultaneously? The surprise for IAFIS is that the risks of conventional IAFIS and of failure in research are not only not positively correlated, but even better, they are *anticorrelated* in their prospects. This is because the main risk for IAFIS is obsolescence caused by new methods, and the main cure for this problem is to find the new methods as quickly as possible.

(c) To eliminate possible ambiguities: We are recommending that the conventional IAFIS plans proceed. But we also strongly urge the FBI to diversify their investments with medium term and long term research tracks.

The FBI needs the capability to take advantage of new and developing technological methods. In fact, the FBI needs to recapture the lead in research devoted to fingerprint identification.

The next section provides an in-depth treatment of our analysis and criteria for reaching these conclusions.

TERM DIVERSIFICATION

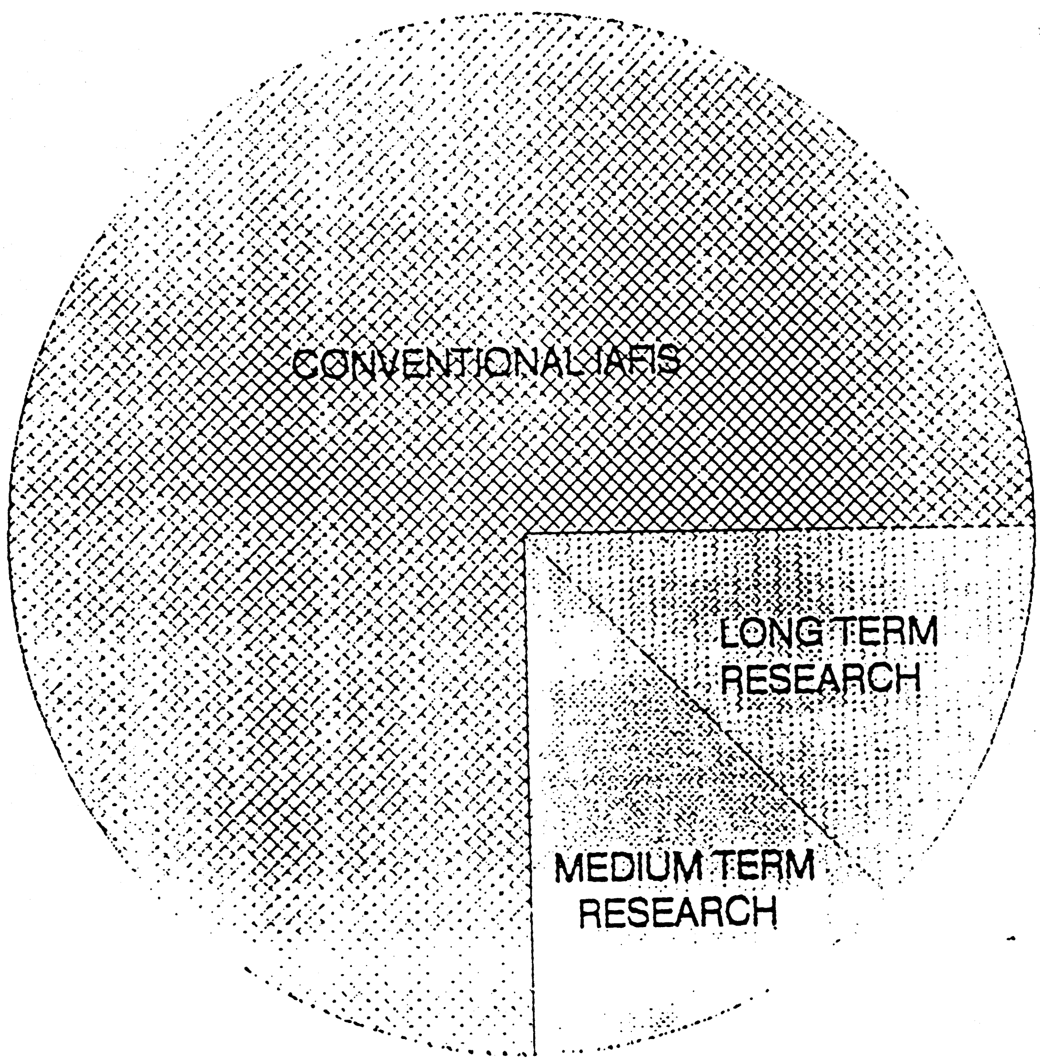

Figure 1: A diversified portfolio of investments in an Automatic Fingerprint Identification System might look like this.

3. The Solution: Research and Development

We have posed a serious problem: how can the FBI switch to the new IAFIS system just a few years from now (by 1994), and yet ensure that this new system is not quickly rendered obsolete or absurdly expensive in comparison to new technology?

Our answer has two components: a modest FBI investment in research into likely new technologies, and a series of small modifications to the IAFIS plan that will make it possible to incorporate the results of such research, whether or not it was supported by the FBI.

Of course it is always easy to call for more scientific research, but we believe the case of fingerprint identification is unusually favorable. Here are the main reasons: (a) serious research on automated fingerprint identification has been in suspended animation for at least a decade; (b) meanwhile there have been highly relevant new developments in mathematics, pattern recognition, engineering and computer science, which could revolutionize applied research on fingerprint identification; (c) consequently it may take a relatively small amount of applied research to radically improve automated fingerprint identification, if the research is in the right areas; (d) without new research the IAFIS will probably be very expensive initially and increasingly expensive over time as the rest of society computerizes and makes far greater demands on the system; (e) with research the IAFIS may be able to avoid or curtail this spiral of costs by finding major reductions in the dominant computational costs; (f) FBI sponsorship of research may lead to government rights to crucial intellectual property, decreasing future costs, and now is a good time to make such an investment.

These arguments are easy to understand and to justify, and were already known to most of the FBI people we talked to. But they leave open two crucial issues: *what are the "right areas"* to support research in, and *what are the "small modifications"* to the IAFIS plan which would allow ~~the research to~~ have an effect? We will focus our report on these matters. We explore them in detail in section 3, sum up our recommendations on promising research areas and IAFIS modification in section 4, and conclude in section 5. In the remainder of this section we will just expand on general arguments (a)-(f) in favor of increased research now.

3.1. Why R & D?

(a) "*Serious research on automated fingerprint identification has been in suspended animation for at least a decade.*" By serious we mean large-scale sustained research into many different approaches by recognized scientists. For example Optical Character Recognition (OCR) gets serious research and is the subject of many current papers in pattern recognition journals. Much of this research is done by people who aren't specifically funded to do OCR, but who find it an interesting test problem for new techniques (such as neural nets) and who hope to seek OCR funding if they have a success. This means that research funding in OCR may have a multiplier effect. By contrast, fingerprint identification is a problem similar to OCR, with considerable intellectual appeal, but it has a much lower visibility in scientific and engineering journals nowadays.

(b) "*Meanwhile there have been highly relevant new developments in mathematics, pattern recognition, engineering and computer science, which could revolutionize applied research on fingerprint ID.*" This will be documented in subsections 3.3 and 3.4 by identifying relevant research areas and developments, as well as mentioning some attractive-sounding but probably irrelevant ones.

(c) "*Consequently it may take a relatively small amount of applied research to radically improve automated fingerprint identification, if the research is in the right areas.*" In other words, nobody's shaken the research tree lately to see if any fingerprint-identification fruit will drop. You may not have to shake very hard.

(d) "*Without new research the IAFIS will probably be very expensive initially and increasingly expensive over time as the rest of society computerizes and makes far greater demands on the system.*" One of the key conclusions of section 3.6 will be that, since automated classification is currently weak to nonexistent, if IAFIS must get along with existing matching algorithms then a large number (hundreds) of special-purpose matching machines is probably required just by the aggregate computing (operations per second) required for IAFIS. This is a very expensive proposition. What is worse, the FBI and MITRE estimates for growth in number of matches to perform per day may be extremely conservative compared to what will actually happen: as image processing and transmission becomes affordable in a rapidly computerizing society, the pent-up demand for fast fingerprint identification will skyrocket and once again leave the FBI behind - unless it choses to take the lead in fingerprint ID and thereby stay ahead of its customers and competitors alike.

(e) "*With research, the IAFIS may be able to avoid or curtail this spiral of costs by finding major reductions in the dominant computational costs.*" For example, automation of almost any noise-resistant classification scheme would yield an enormous reduction in the number of matches per day required, and therefore in the total computational cost. Also substantial improvements in the technology of matching may be available, though here the savings is probably not so much in number of computer instructions per match (currently only two million) but in the chip cost per instruction and the cumulative time required to do them all serially. This indicates opportunities for chip designers. These issues are discussed in more detail in section 3.4.

(f) "*FBI sponsorship of research may lead to government rights to crucial intellectual property, decreasing future costs, and now is a good time to make such an investment.*" This is a matter for the lawyers, whom we are not.

3.2. Computational Characteristics of IAFIS

Here we want to expose some essential characteristics of the IAFIS fingerprint identification problem from a computational point of view.

First, IAFIS is a **pattern matching** problem. That is, we must determine whether two fingerprints are identical or not despite substantial image noise including distortions, different inking, missing and extra regions, image shift and rotation, etc. These problems are addressed by matching algorithms which are currently functional but leave room for improvement both in accuracy and speed. The FBI's current Printrak matchers are probably somewhat more expensive than the HO39 matching algorithm, which is estimated[1] to be implementable on a serial computer using two million instructions per match.

Second, IAFIS is a **database** problem. Matching every incoming print against every possible database print, using the fastest matchers foreseeable, is exhorbitantly expensive. Conventional databases are *indexed* to prevent such complete database scans, but the fingerprint database is not easy to index without interfering with matching. This problem is conventionally dealt with by *classification* of a print, and/or a 10-print card, into many bins which theoretically have zero overlap and in practice have low overlap (few "references" to next-~~most-likely bins are required~~). The important quantities to minimize are the bin sizes and their probability of overlap. *It is of utmost importance to realize that classification is far behind matching in its degree of automation.*

Conventional IAFIS plans call for pattern-level classification (meaning each finger is put in one of 6-10 bins based on global patterns including "whorl", "tented arch", "ulnar loop" etc.) since that is what is likely to make a minutia-based matching system succeed, using current technology. This is a conservative approach with large bin sizes and large computational expense in matching, but even this level of classification apparently has not been reliably automated (see the "MITRE proposal"[2]). Smaller bin sizes would be highly desirable but would require new research progress in classification and indexing, perhaps in automating manual classification methods and perhaps in totally new methods.

Third, IAFIS is a **supercomputing** problem. That is, a very powerful computer is required - perhaps impossibly so given a 1994 start date, and assuming no research breakthroughs to cut down the size of the problem. Let us crudely estimate the number of computer instructions per second required for the conventional (proposed minutia matching and pattern-level classifying) IAFIS, just for 10-print miniutia-match searches of the criminal database:

# of instructions/match = at least 2 million.

("# of" means "number of".)

Note: as discussed above, this is estimated for HO39, and could increase substantially for improved matchers. Unfortunately we do not know the proportion of floating-point instructions executed in HO39, and thus cannot rate IAFIS in Floating Point Operations per Second (FLOPS). But for most computers the maximum FLOPS rating is a fraction, between about one-tenth and one, of the maximum instructions/sec figure.

# of incoming cards/second = (# of cards/day)/(#of seconds/day) = (about 78,500) / 86,400
= about 0.91 .

Note: According to the MITRE proposal (table 7-1), the average day's 10-print card workload is expected to be 78,491 cards by Dec. 1995, which date is fairly early in the expected operational life of IAFIS hardware. During FY 1990 this same workload figure averaged 33,000 with a peak of 50,000. The 10-print "cards", of course, may be partly or entirely electronic.

# of candidate database cards/incoming card = at least 91,500 .

Note: This assumes that the criminal database will grow to 30.5 million by the end of 1995, as predicted in the MITRE proposal's table 7-2. At the end of 1990 there were 23.2 million cards in the criminal database. It also assumes the effectiveness of age, sex and pattern-level classification which R. T. Moore[3] calculated for an 18 million card criminal database in 1988, which would have resulted in 54,000 candidate database cards/incoming 10-print card.

# of fingerprint matches/candidate database card = at least 1.7 .

Note: again this figure is from Moore's memo. For evolutionary reasons, it must lie between one and ten.

Putting these numbers together, we find the total number of computer instructions per second required for this one function of IAFIS:

# of instructions/sec = (# of instructions/match) x (# of matches/candidate db card) x (# of candidate db cards/incoming card) x (# of incoming cards/sec)

= at least 283 billion.

Given that the quality of the matcher and the 10-print and especially the latent workloads will probably increase substantially, we find it plausible that **conventional IAFIS is actually a "teraflop" project** (it will require a computers capable of nearly 1 trillion floating point operations/sec). This kind of computing power is the goal of a very ambitious multi-agency government program, but even with stunning success in this program no such general-purpose computer is expected by 1994.[4] For this reason we find that special-purpose matchers are required for conventional IAFIS.

3.3. Research Areas to Avoid

It is likely that various irrelevant but trendy research areas will be brought forward whenever a substantial new research contracting opportunity like the IAFIS research track is publicized. In this connection we would warn against *fractals, chaos,* and *fuzzy logic* as these areas are presently consitituted. In addition, certain kinds of neural networks will bring more heat than light to the subject. In particular, those neural networks which *rely mainly on a Euclidean distance metric* to measure similarity between two patterns, or on a distance metric which the neural network does not specify and is usually taken to be Euclidean, are not likely to address the central problems of fingerprint distortion, rotation, translation, and missing/extra regions. Coming up with a neural network that knows which images should be "near" to or "far" from which other ones, while remaining computationally affordable, is a major challenge not to be glossed over. The affected neural networks include the pure Content Addressable Memory (CAM), Adaptive Resonance Theory (ART), Learning Vector Quantization (LVQ), Radial Basis Functions (RBF), and Self-Organizing Feature Maps.[1]

Naturally these points may be controversial among the adherents of the methods we mention, and we could be proven wrong by a convincing pilot AFIS experiment (including fingerprint distortion and noise) using any one of these areas of expertise. But all other things being equal, ~~we would be especially~~ skeptical of these areas right now.

3.4. Research Areas of Greatest Potential

By contrast, it is our pleasant duty to inform the FBI of many research areas that appear ripe for application to AFIS. The four main categories we found are described, together with their computational advantages, in subsections 3.4.1 - 3.4.4 respectively. One particular area appears so promising to us that we'd like to follow it up ourselves, and is described in 3.4.5. The four main categories and several possible methods in each category are listed in a table format in 3.4.6, showing which AFIS task applications and what computational advantages each method may have.

It is important to remember that the areas outlined below are not mutually exclusive, and several of them could be combined even within one algorithm for one task.

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[1] We have encountered several researchers who use ART or LVQ with other distance metrics besides Euclidean, and indeed this seems like a subsantial improvement on the original methods. This does not alter the fact that the choice of similarity metric is the hard part of the design, nor soften our stance against the invocation of these methods as a substative step towards pattern recognition, when in fact they play only a supporting role.

3.4.1. Trainable Neural Networks

One very important and obvious area of research, which has arisen since the last wave of activity in AFIS research, is the development of effective training algorithms for artificial neural networks (ANN's). The "back-propagation" algorithm[5] allows a neural network to learn how to perform some computations by training on a large set of example input/output pairs, and then extrapolating to novel inputs. In this way neural networks can learn how to solve a variety of pattern recognition problems. Machine learning had been progressing very slowly as a part of Artificial Intelligence before the advent of these neural networks, and they constitute a major breakthough in machine learning. The backpropagation algorithm is often far from the best one nowadays, but it has revolutionized the field.

Trainable neural networks could be highly relevant to AFIS since one would like to have a network learn the intricacies of real fingerprint noise, as well as to refine its own intrinsic (unlearned) ability to do inexact matching and pattern recognition. The major problems that arise are: scaling up to large images (e.g. roughly 700 x 500 x 8bit fingerprint images), scaling up to large databases of such images, and asserting human control over or at least understanding of the assumptions behind the network (for example, to give it hints for use in learning).

One can argue that the problem of scaling to large data bases is handled by the basic design of classification and matching tasks, each of which just involves one or two (processed) images and is to be repeated as necessary. This optimistic argument will have to be verified for any neural network methods developed for AFIS, but it is plausible. However, the problem of scaling up to large images is not so easily dismissed because most neural networks are trained on 10-100 inputs, not 300,000! This is an enormous difference in scale. So the standard techniques and experience with neural networks may be highly misleading.

Fortunately, there are neural network architectures (designs) specifically tuned for image analysis. They form a small part of the neural network field, but they are the interesting part for AFIS. Most of them are dealt with in the following sections because of additional computational characteristics beyond trainability, but one simple neural architecture for vision can be explained right away. Cottrell, Munro and Zipser[6] have introduced a two-part training procedure for image classification or discrimination networks. In the first stage, an image drawn from a set of real images is fed forward into a small internal layer of neurons which must encode as much detail as they can, and then feed that information forward into a final image layer which is scored according to how well the original image is reconstructed. This network simply tries to perform image compression for the class of images to be classified. Once this coding layer has learned as much as it is going to about the statistics of the images to be classified, a new final layer with just a few neurons is connected up to the internal layer and trained to provide the classifications or discriminations desired. For example, this final layer has been trained to determine the sex, emotional state and identity of a human being from a corresponding 64 x 64 pixel gray-scale face image[7]. This image size is still a factor of 50 or so smaller than a fingerprint image, and the problem was intrinsically much easier than fingerprint identification, but it is quite an impressive demonstration considering how little structure was designed into the network.

Other neural network approaches to image processing already known to the Bureau include the Optical Character Recognition networks of Wilson et al. at NIST, and the MITRE suggestions for image processing and matching neural networks. As mentioned above, most of the neural net examples we give will be in the following sections on relaxation and scale space algorithms, although such algorithms are not required to be neural networks.

3.4.2. Relaxation Algorithms

(a) We give very high marks to Relaxation Algorithms and their potential applications to image processing. In fact, this area includes our own method "GRAPH MATCHING NEURAL NETS AND SPHERE-OF-INFLUENCE GRAPHS". This method combines our own expertise in neural nets and graph theory to present a new, innovative method with great potential. More details about our method are included in 3.4.5.

(b) The methods covered in this section can be likened to the behavior of an old rubber band, which can be stretched into a wide variety of shapes but, when released, always relaxes to one particular shape that it "remembers". Likewise we can design mathematical "rubber bands" whose computational behavior is to relax towards any idealized fingerprint image, as much as possible given that a real-world noisy fingerprint image is "pulling" on it. The difference from real rubber bands is that the relaxation process happens in a computer and the properties of the rubber bands are directly determined by a human designer instead of by the physics of materials. In other words relaxation algorithms are based on a detailed "model" whose assumptions are under the control of a human designer.

Algorithms that work this way are increasingly common both in computer vision and in neural networks. One of their greatest attractions is that they can often be implemented directly in fast, cheap, massively parallel silicon chips; this has the potential to greatly decrease the cost of the required hardware. Of even greater importance is the tendency of a relaxation algorithm to "restore" many noisy states to a few relatively relaxed ones, giving rise to an intrinsic stability against certain kinds of noise. Naturally the nature of this noise insensitivity must be designed into the algorithm if it is to include characteristic fingerprint distortions, inking variations, and so on. This noise insensitivity is part of the model underlying a relaxation algorithm, and it is one of the attractive technical features of such algorithms that they are usually "model-based".

In image processing, such relaxation algorithms would act to clean up noisy fingerprint images and to find their associated minutia maps by locating branches and ridge endings in the cleaned up, idealized image. In matching, one might instead try to distort one minutia map as little as possible while making it match to another, and then measure the stretching energy to score the match as likely or unlikely. Neural networks and other relaxation algorithms have already been invented to do both image processing and matching as just described, and now seem ripe for application to fingerprint identification.

(c) The relaxation process results in a collection of curves which can then be used to detect specific pieces of information from the image. Some particular curve algorithms include:

Snakes[8] and Splines; Elastic Networks[9]; and Zucker's biomorphic spline network which has already been applied to fingerprint images[10] as shown in figure 2. Smoothed Local Symmetries[11] comprise another method with great potential for finding and also classifying curves; this suggests their use in fingerprint classificiation. We met with Michael Brady (Oxford University) to discuss potential fingerprint applications of recent research in this area. Cheap, parallel circuit implementation (VLSI chips) of any of these methods appears possible.[12,13]

(d) Snakes, Splines, Zucker's Splines and Elastic Nets look good for image processing, but we are unsure of their potential for classification. Smoothed Local Symmetries and our own Graph Matching Nets and Sphere-of-Influence Graphs appear to have significant potential for classification. These last two methods would not play a role in image processing. We are suggesting that some, but not necessarily all of these methods should be pursued for extracting curves from images.

(e) Within relaxation algorithms we recommend only our method, Graph Matching and SIGS, for matching. This method is discussed in more detail in section 3.4.5. Briefly, it provides a "graph" representation of a set of features (such as minutiae) and the relationships between them which is insensitive to distortions, and a neural net capable of matching these graphs despite substantial noise. The other relaxation methods are too computation intensive or not "smart" enough in their choice of image representation. Finally we think that Graph Matching and SIGS could be applied to verification, because verification is a kind of super-accurate matching, but more research would be needed here. We do not see the other methods in this group as being applicable to the verification problem.

(f) Some advantages of relaxation methods include the fact that they are model-based and noise resistant. Also, it appears that these methods could be used in conjunction with fast, cheap special purpose chips, possibly using analog VLSI (Very Large Scale Integration) to build chips which could converge in 10-100 microseconds per match[14]. We believe that this is an especially important feature. For example, graph-matching chips might allow the FBI to house the equivalent of 1000 matchers in a single cabinet (or the equivalent space for one current matcher). Since conventional matchers are expected to be one of the most expensive parts of IAFIS, this would be a development of major importance.

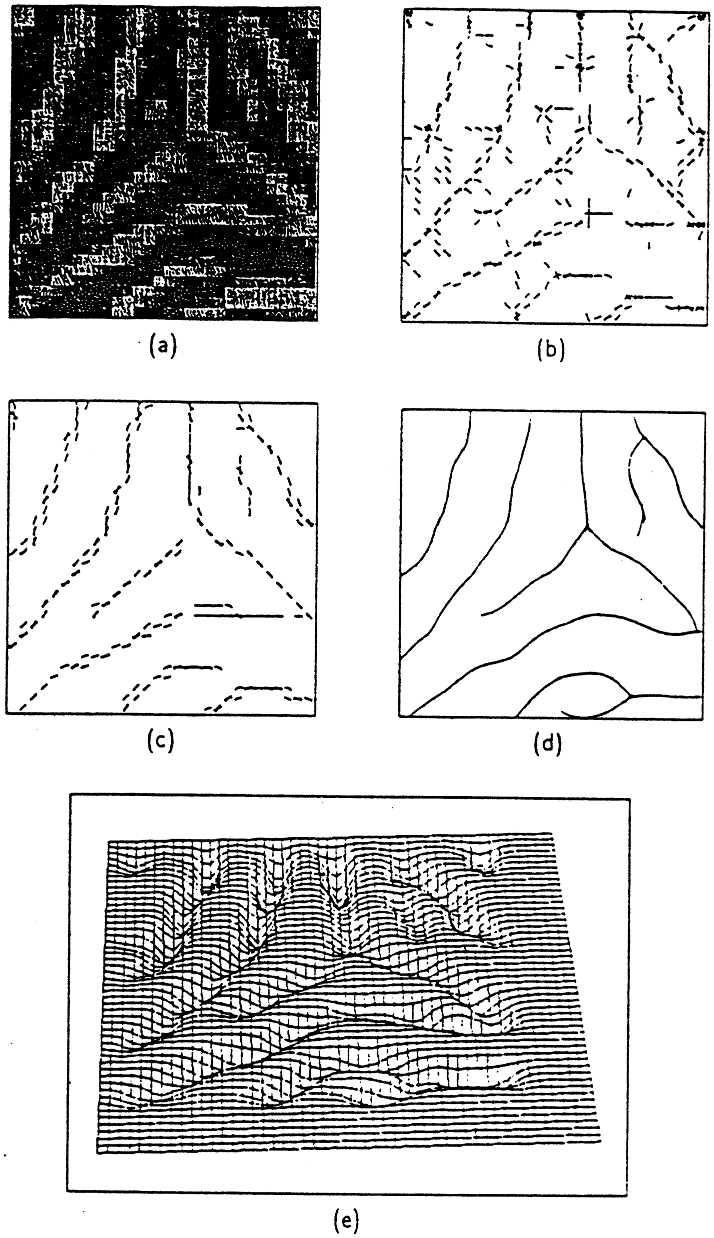
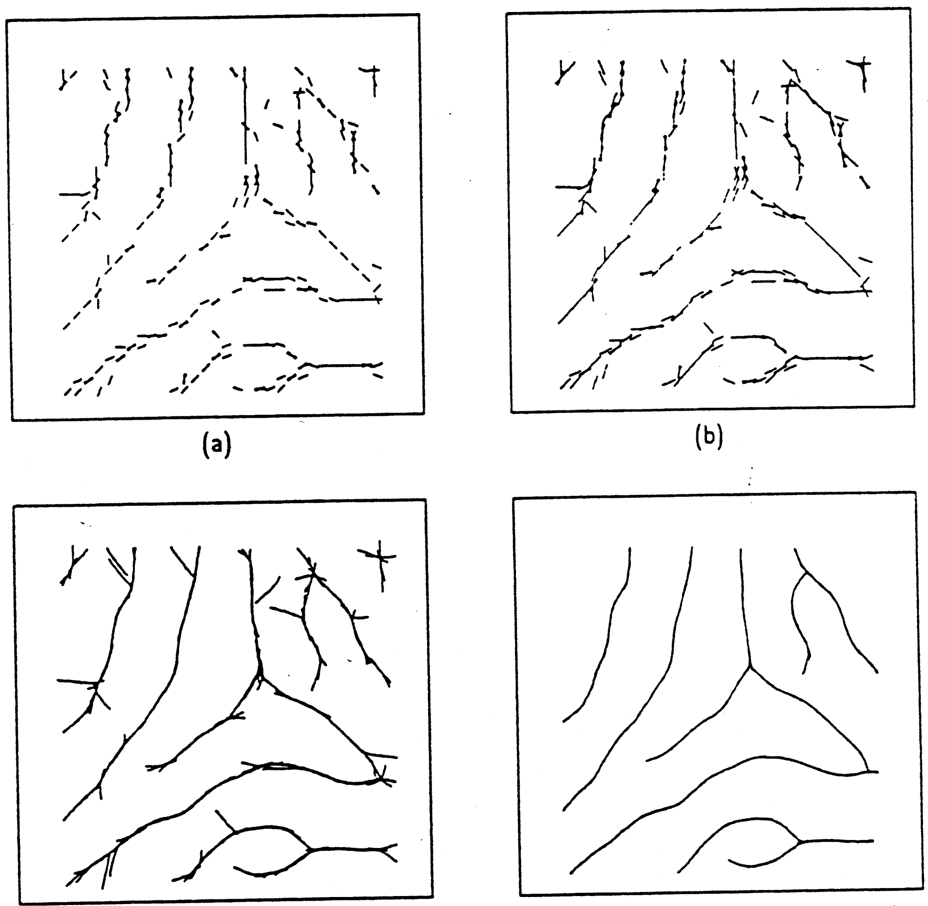


Figure 2: Zucker et al.'s spline neural networks applied to fingerprint image processing.

An illustration of the different stages of curve detection. In (a) we show a section of a fingerprint image; note the smooth curves and discontinuities around the "Y" in the center. (b) Graphical illustration of the initial information, or those orientation/curvature hypotheses resulting from convolutions above the noise level. (c) The discrete tangent field resulting from the relaxation process after 2 iterations; note that most of the spurious initial responses have been eliminated. (d) Final snake positions, or coverings of the global curves. (e) The potential distribution constructed from the entries in the tangent field.



(a) (b) (c) (d)

Figure 4: Illustration of the splines in motion. Initially, each spline is born at a tangent field location, with unit length. Then, according to the potential distribution shown in figure 1e, the splines migrate in position (to find minima in the distribution) and in length, so that they overlap and fill in short gaps. At convergence, the length of each spline has tripled. Not shown is the fact that each spline is born with a different "color," and that, as they overlap, the colors equilibrate to a unique value for the entire covering of each global curve. Also, those splines that migrate to positions unsupported by the potential distribution are eliminated at convergence. (a) Initial distribution; (b) and (c) intermediate iterations; (d) final convergence. Physiologically one might think of the spline computations as being supported by localized dendric or dendro-dendritic interactions.

(g) The relaxation algorithms which are also neural networks are not yet, by and large, trained, but there is good reason to think that they soon will be since a number of training algorithms exist and are being refined. The main obstacle is the lack of massively parallel or analog circuit implementations of such networks, which makes simultaneous relaxation and training quite expensive by comparison with training feed-forward neural nets (including scale-space feed-forward nets). We expect these obstacles to be removed over the next few years. By contrast we do not think it will be so straightforward to add the advantages of "model-based" design, including the specification of the nature of the noise to be overcome, to other kinds of neural networks.

(h) Smoothed Local Symmetries looks promising for classification but, as noted in the POTENTIAL APPLICABILITY TABLE, needs a bit more research before the Bureau actively explores its applications to the fingerprint problem.

(i) As indicated in the TABLE and the above discussion, we are very enthusiastic about our own method - Graph Matching Neural Nets and Sphere-of-Influence Graphs. Of the methods considered under Relaxation Algorithms we feel that it is the one method offering the greatest potential for further pursuit by the FBI.

3.4.3. Scale-Space Algorithms

(a) Scale-space algorithms aim chiefly to "scale up" to large images. They are very valuable because such scaling is essential but can be surprisingly hard to achieve, especially for trainable neural nets which tend not to have a lot of scaling structure build in. The basic idea is to consider not only the original image, but also a whole "pyramid" of images at coarser and coarser scales or levels of resolutions, each image more blurred but smaller and more tractable than the last. Scale-space methods have received wide attention in various applications. In the paragraphs that follow we present some of the ones that seem most suitable.

(b) Bipyramidal neural nets are characterized by their ability to deal with various levels of decreasing spatial resolution, as in a pyramid, which simultaneously increasing their resolution in some other important feature space. The simplest well-know example is the Fast Fourier Transform, which proceeds through a sequence of levels which cut spatial resolution in half while doubling frequency resolution. Some important neural net examples are LeCun's Zip Code Reader[15] and Baldi's Fingerprint Network. Figure 3 shows the overall design or "architecture" of LeCun's network.

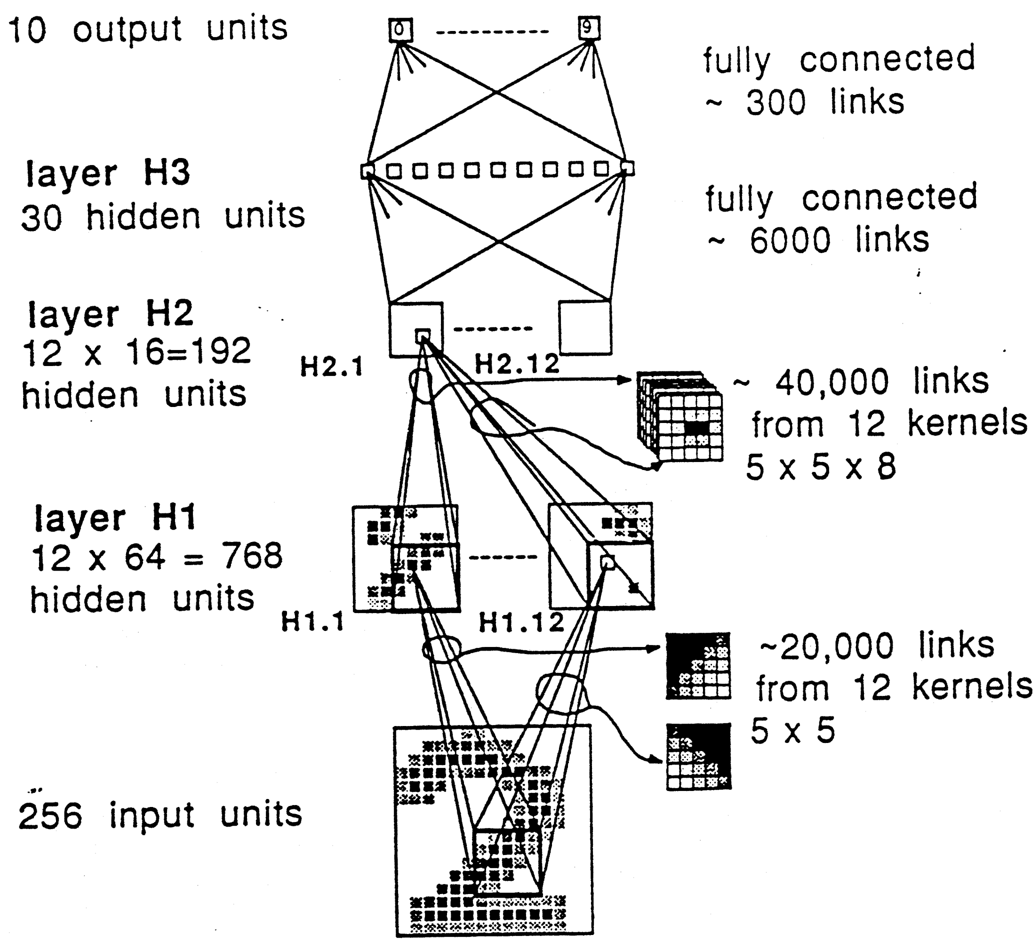


Figure 3: Bipyramidal network for zip code recognition.

Log mean squared error (MSE) (top) and raw error rate (bottom) versus number of training passes.

This type of design has already been applied to fingerprint identification, with good success on a small database, by P. Baldi and his startup company ("NetID" of Palo Alto, CA). Baldi quotes[16] *zero test error* on a database of 2-300 fingerprint image pairs obtained optically (by total internal reflection). Baldi also reports that the learned receptive fields in the network appear to have nothing to do with conventional minutiae, but rather concentrate on ridge properties. The achievement is remarkable since it shows requires the neural network to have learned both image processing and matching in some form. Thus image processing and matching are areas where bipyramidal nets have great potential. More research would be needed for analyzing their usefulness in classification.

(c) Wavelets have advanced and also become extremely popular in the last few years[17] and, in fact, have already been considered as a possible method for image compression by the FBI. It is important to note that only "linear" wavelet transforms have been considered so far; this distinguishes them from neural nets. Wavelets are a recent improvement to the classic idea of Gabor wave packets or Gabor filters, and the older versions of the idea may be just as good for the image processing task. So we lump Gabor filters and wavelets together in the Potential Applicability Table. These methods do not appear especially relevant to other AFIS tasks beyond image processing.

(d) Another area of strong potential would be to design a hybrid method combining wavelets with suitable neural nets. In this case one would have a method that could be applied to image processing and perhaps classification as well, since an algorithm can make both intermediate and final *decisions* with added nonlinear elements such as an artificial neurons. Such a hybrid would also be a strong contender when viewed in the areas of training and scaling. Although more research is needed before actively pursuing this method, it is tantalizing in its potential.

(e) As with most methods, scale-space algorithms do not receive high marks for every category. As stated above, we see their greatest potential in their potential application to image processing. Verification is the one area where these algorithms do not provide much promise. However, each of the scale-space algorithms described above have the desirable feature of going beyond, or at least not committing to, Euclidean measures of similarity; so they have some chance of being distortion invariant. It should be noted that one weakness of these methods is that they are not model-based, making it considerably harder to control the types of noise immunity they have.

(f) More research is needed to explore the adaptability of these methods to chips. Likewise, robustness of bipyramids requires more research. We are unsure of this issue as it relates to wavelets. In summary, we feel that Bipyramids and Gabor filters/Wavelets transforms are definitely worthy of further pursuit by the FBI. Both are relevant for the image processing task, and the bipyramidal neural nets are also relevant for matching and perhaps classification. It would take more research to make this determination for the Wavelet-Neural Net Hybrid method, which however may be applicable to the classification task..

3.4.4. Examiner Expertise

(a) Our background investigations, particularly in the area of classification, included in-depth interviews and discussions with very experienced tech and latent examiners. On one of our early tours of the Ident process we observed that the experienced examiner appeared to use his or her own highly refined searching process to make idents and non-idents, over and above the textbook approach presented in examiner training.

(b) As a result of our discussions with experienced examiners we feel that the special, customized and sometimes subtle decision making tools expressed by such examiners reveal skills and insights that could play a role in further developments in automated fingerprint identification. Algorithms designers have interviewed expert examiners on many previous occasions, yet the expertise has never been adequately expressed in procedural form such as an expert system. Such a procedural expression of actual human strategies, however inefficiently it might run on a computer, would be of some help to algorithm designers. Further research into this area seems to be fully warranted.

(c) We believe that a thorough and complete investigation into examiner expertise could be effective in the specific concentrations devoted to classification, matching, verification and image processing itself. It is somewhat doubtful that information from examiner debriefing could be applied to training an artificial neural net or other algorithm. Also, it appears unlikely that chips could be adapted to this method. However, methods developed from examiner expertise could enhance robustness and could lead to alternate model-based approaches which are euclidean free.

(d) How can examiner expertise be utilized? One suggestion is to record protocols applied by expert examiners and to apply these records in the design of an expert system. The goal would be to *proceduralize* the examiner's expertise and thereby create a deeper understanding of it. Expert systems are currently applied in other areas such as medical diagnosis and machinery diagnostics. It has been our observation that the Ident process is also a form of "DIAGNOSIS". Naturally, such an expert system, in order to be functional, would only represent some simplified set of "rules" or "opinions" demonstrated by the expert system. It is our further suggestion that such an expert system might be best utilized as a component of a HYBRID EXPERT SYSTEM-NEURAL NETWORK. In such a system the expert system component would serve as the ideal, to be *approximated* by a neural network capable of implementing a limited form of expert system, and able to be implemented in turn by a fast VLSI circuit. Such restricted neural net/expert systems have been the subject of encouraging research progress[18].

(e) Another use for examiner expertise is in the design of coding or representation schemes for fingerprint images, in order to make use of perceptually salient features or coincidences beyond the usual minutiae. One example of previous work in this direction is the string coding scheme of Sparrow and Sparrow[19], which was designed to take advantage of string matching algorithms.

(f) We would like to point out that all of our interviews and meetings in this area generated much enthusiasm and further discussions. The possibility of further pursuit into examiner expertise was extremely well received. We also feel that this area should be actively pursued by the FBI, particularly with regard to the need for further research in classification.

3.4.5. Our Favorite: Graph Matching

(a) As indicated in the introduction to this section, we have determined one area of research to be particularly promising. This method presents our own research approach utilizing our combined backgrounds in graph theory and neural networks. In our method we combine SPHERE-OF-INFLUENCE GRAPHS with GRAPH MATCHING NEURAL NETS.

(b) Sphere-of-influence graphs comprise a relatively new set of graphs. They are intended to capture low-level perceptual structures of visual scenes consisting of dot patterns[20]. A sphere-of-influence graph, G(S) is formed from a set of points S in the following way. To each point of S we assign an open ball centered at that point of radius equal to the smallest distance from that point to any other point of S. The vertex set of G(S) is S. Two vertices are adjacent in the sphere-of-influence graph whenever their open balls intersect. Examples of sphere-of-influence graphs can be seen in Figure 4.

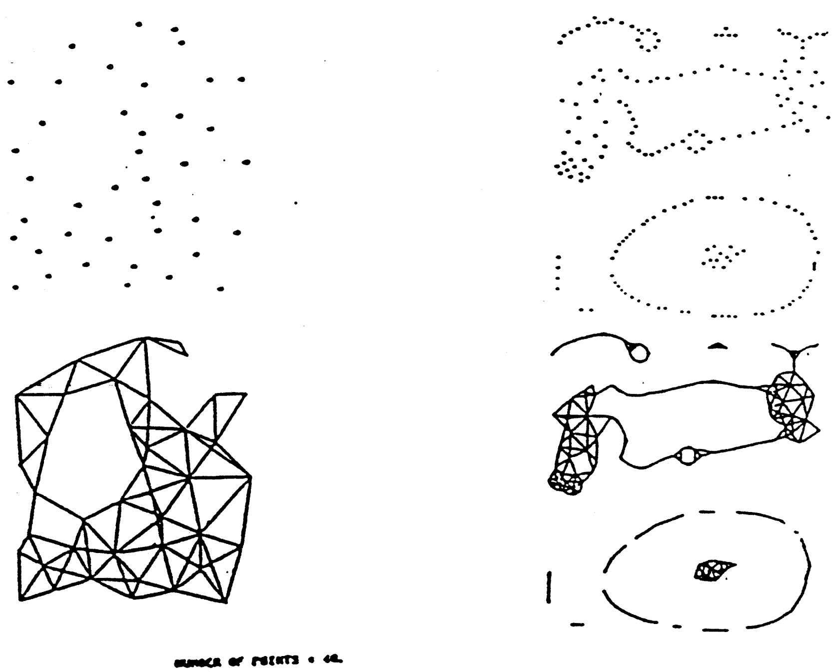


Figure 4: Sphere-of-influence graphs, highlighting perceptually salient aspects of feature location patterns. One application of such graphs would be to represent minutia maps by encoding the relationships between nearby minutiae in a graph, to be matched to other such graphs.

(c) We propose to apply sphere-of-influence graphs to minutiae maps. From these illustrations one can note that perceptually salient groups of dots become even more distinct in the corresponding sphere-of-influence graph. There are various specific benefits of sphere-of-influence graphs over previous methods for capturing visual scenes in computer vision.

(d) SIGS deliver either the "internal" structure or skeleton of a form or the "external form" as a function of what the data looks like. Secondly, it outputs a connected graph or a collection of disconnected pieces. It performs all of the above without any requisite tuning of parameters. Finally, it can be computed efficiently. We see our approach as potentially very successful in the areas of classification, matching, and perhaps even verification.

(e) We propose to use SIGs for image representation of minutiae. The second part this method consists in the application of relaxation neural networks for *matching* such labeled graphs. Due to the sophisticated distance metric associated with SIGs, we believe that *classification* can be done effectively via clustering. This type of classification would be especially advantageous since it would be a natural extension of the matching algorithm, rather than a completely separate scheme likely to conflict with matching. Because graphs can explicitly represent relationships between features, the matching method is unusually tolerant of distortions, translations, and rotations; this addresses one of the major drawbacks of other approaches. SIGs function as a greater insurance when dealing with missing or extra features as well as distortion. Subgraphs of SIGs and their relationships also provide further information. More research is needed to apply our method to *verification*, but we believe that it has greater potential for success here than many other approaches. That is because the difficulty in verification is due to the requirement for very high accuracy in matching and smart matching is the main strength of the graph-based approach compared to other methods.

(f) A small minority of neural network researchers has concentrated on graph-matching for much the reasons we outlined above[21,22]. Among them, the work of C. von der Malsberg is notable. In one investigation[23] his group showed how to combine relaxational graph-matching with a scale-space approach and thereby achieved a neural network with some ability to recognize faces despite severe distortions such as three-dimensional rotations. This work may indicate a productive way to label the graphs that appear in a graph-matching neural network.

(g) As indicated in the Potential Applicability Table, we give good marks to the SIG/graph-matching method in such computational characteristics as trainability, scalability and the facts that the approach is model-based and Euclidean-free. In addition, it looks possible to implement cheap, fast special-purpose chips for our approach. The method is unique in being directly aimed at achieving matching in a manner invariant to characteristic fingerprint noise such as distortions and missing or extra features. It is likely to be applicable to classification as well, in a way that is unusually compatable matching process. Finally we think that Graph Matching and SIGS could be applied to verification, because verification is a kind of super-accurate matching, but more research would be needed here.

3.4.6. Potential Applicability Table

In the following table, the various new research areas that may give rise to new AFIS methods are listed as rows. The columns correspond to important attributes of these approaches: the first four columns, to the relevance for four major AFIS tasks we have identified; the next six columns, to advantageous computational characteristics; and the final column, to a recommendation about the proper level of interest in persuing each approach at this time.

We review here the meanings of the six "favorable computational characteristics". "Trainability" is the abilitiy of an algorithm to learn from experience (called training) according to demonstrated learning algorithms. "Scalability" is the ability of the technique to scale up to large images, which is necessary but lacking in many algorithms that originate outside of computer vision or image processing. "Model based" means that an algorithm is based on an underlying model of the image structure whose assumptions are under the control of a human designer, as discussed above in the section on relaxation. "Fprint robust" means that an approach has yielded algorithms whose robustness to actual fingerprint variations and noise *has already been demonstrated*. "Cheap chips" refers to the likely implementability of a class of algorithms in silicon chips that will vastly reduce the cost of a computation. "Euclid free" is shorthand notation for the absence of any crippling assumption of ordinary Euclidean distance as the measure of pattern similarity where some much more sophisticated, distortion-invariant idea of similarity is needed.

We found it all too likely that potential contractors for the IAFIS project would strive to avoid openness in an effort to eliminate future competition. For example, it is our understanding that some potential contractors are resistant to the idea of establishing standards or even publishing the specification for the interface between image processing and matching modules. *This kind of closed, fully proprietary approach is a threat to the entire IAFIS program.* The reason is simple: insufficient "openness" will prevent IAFIS from benefitting from many competing research efforts such as those provided by the proposed research track; and without such broad-based and diverse research, as we have argued repeatedly, IAFIS is inherently a very risky program. Fortunately, openness in both hardware and software has come to almost all areas of the computer industry over the last decade[27]. This has the effect of maximizing the adaptability of installed hardware to new developments in both hardware and software, and is so appreciated by customers that most manufacturers have been forced into making open systems to stay competitive. We simply propose to extend openness into the AFIS application area, by force of FBI's considerable prestige and purchasing power in this marketplace.

We now proceed to outline how the IAFIS requirements may be changed to ensure openness to new fingerprint identification methods. This involves three elements discussed in the next three subsections: enforced task modularity, FBI services to challengers of the reigning methods, and the necessity of keeping the classification scheme flexible.

3.5.1. Enforcing Task Modularity

We want to ensure continual openness to new automated methods in fingerprint identification. It is unlikely that any one idea or research direction will apply equally well to the four main tasks we have identified: image processing, classification, matching and verification. Most developments would substantially improve only one or two of these areas, because they seem to have little in common computationally. So if IAFIS is to be open to new developments, it must be able to upgrade the algorthms used for these four tasks separately and independently, holding three areas fixed while changing the fourth. This requires a rigid enforcement of *task modularity* in IAFIS, meaning that these four tasks should interact only through relatively stable, well-defined interfaces. This is a common principle in software engineering: good programmers try to achieve modularity in their programs so that modifications in one area will not require modifications in the others. But here we are asking not only for modularity but also for openness, so the *IAFIS design must allow alternative methods for each task to be installed at any time for extended testing or to actually replace the previous method.*

In order to allow competition between alternative versions of each task, *it is vital that all the interfaces between tasks be completely public.* It would be nice to have the interfaces standardized as well, except that this could inhibit some technical directions of development. For example image processing and matching can be traded off, with a more extensive image processing job making up for a weaker matcher or vice versa. A minimal image processor might output a bare minutia map, while a stronger one might add labels such as ridge counts between neighboring minutia to the map and thus ease the burden on the matcher. So it may be wise to allow different companies or research groups to define their own interfaces between tasks, *providing always that these interfaces are made public* for use by later challengers with an even better method that can be made to work with some or all of the same interfaces.

We anticipate some resistance on this point from existing conventional AFIS vendors but we believe that *this is a battle the FBI must win*, even at substantial expense in both money and initial IAFIS system performance. The reason a performance hit is acceptable is that task-level openness allows far more performance improvement subsequently (or immediately, given some cooperation between several contractors) than a closed system can hope to acheive. This is very important to the research track and thus to reducing IAFIS's risk of obsolescence. But a performance hit is not too likely, once it is made clear to potential contractors (well established in AFIS and otherwise) that the FBI is going to use its fingerprint identification prestige and purchasing power to introduce task-level openness into AFIS, and that there is money to be made by going along. In fact, the existing systems already seem to be quite modular; the only question is whether FBI's contractors can be persuaded to publish their interfaces. *So task-level modularity and openness should be an absolute IAFIS requirement, not just an attractive feature for deciding between otherwise similar proposals.*

In addition to enabling IAFIS to capitalize on possible research advances in automated fingerprint processing, there is another benefit of requiring modularity and openness at the task level which we should mention. FBI sponsorship of competition on the scale of small pieces of an identification system (as opposed to competition between entire systems) could directly drive down the initial system's cost. That is partly because each task will be subject to at least the threat of competition from the very outset, partly because more varied and specialized compteting contractors may be attracted if there are more numerous competitive niches, and partly because the economies of scale sometimes work in reverse for large software systems.[28]

Finally, we may not be able to foresee some important new ways in which openness could benefit IAFIS, but which potential contractors are able to see and act on. Consequently, *openness beyond the task level* (in fingerprint identification methods) should be considered as an optional but potentially important feature in an IAFIS proposal, which *may outweigh poorer initial ~~demonstrated~~ ~~performance~~*. For example, openness at a scale finer than the task level might be achieved by competition between cleverly defined subtasks. On the other hand enforcing modularity at a finer scale might actually work against openness by excluding methods that don't easily split up along the proposed fine-scale boundaries.

3.5.2. Services to Potential Challengers

One effective way to push AFIS research forward is simply to lower the mundane barriers to entering the AFIS research game: obtaining a fingerprint data base and access to the details of some existing methods (especially for matching). If these materials are made readily available, IAFIS may even recieve a considerable amount of *free research* from experts in pattern recognition, neural networks, etc. who are doing pilot studies or want to find applications for new techniques developed with other support. To this end, *the FBI should make publicly available (1) the source code for some existing matcher (such as HO39) and perhaps for some existing algorithms for the other tasks as well, and (2) a sizable database of matching fingerprint pairs*. The database could be evenly divided into a training section and an unlabelled testing section; the testing section would be provided without the labelling that tells which fingerprint should be matched to which. In this way the FBI could *filter* new methods according to their score on the testing set, and provide further support services only to the most promising methods for each task.

New algorithms that appear especially promising as judged by the publicly available filtering database *should be given the opportunity to challenge (be tested on) even larger databases up to and including including the entire FBI fingerprint image database, using IAFIS computers in much the same way that installed IAFIS algorithms do.* Researchers would be encouraged to diagnose problems with their methods and take detailed statistics on performance problems. Since the IAFIS software design must be open , this challenge procedure will not involve too much reprogramming of the challenging algorithms. It poses a computer security problem, which can be handled and which is minor compared to the problem of IAFIS obsolescence which it may prevent.

Finally, we suggest an *annual review to determine which algorithms should actually be used in IAFIS* during the coming year. All algorithms for all four tasks that have performed well enough on challenges would be eligible (along with the current and previous best methods actually used in IAFIS) to be retested in various combinations, so that the FBI could determine whether it wanted to switch to any of the new methods, and could enter into negotiations to do so if it hadnt already. This mix-and-match testing would require no reprogramming of the challenger algorithms at all, if the IAFIS system design is as modular and open as it is required to be.

3.5.3. Classificiation is Crucial

One of the strongest recommendations of those involved in the States AFIS systems, when reviewing the FBI s existing AFIS system, was a switch from full classification or NCIC classification to the the much easier and coarser pattern-level classification in conjunction with minutia-based matchers[29]. (Pattern-level classification means classifying each finger into certain broad topological categories such as whorl, arch, tented arch, etc.) This recommendation was accepted for example in the MITRE proposal for a largely conventional IAFIS[30]. We also have reinforced this recommendation by insisting that conventional IAFIS (minutia matching and pattern-level classification) must proceed until something better is fully demonstrated. However, we want to make a crucial distinction between pattern-level classification in conventional IAFIS, which is the default method, and new classification algorithms contributed by the research track. These new new new algorithms must be free to classify in any way and to any degree of fineness that proves effective (in conjunction with any matching algorithm). Furthermore, these algorithms may prove much more cost-effective than pattern-level classification (manual or automated) and may very well *replace pattern-level classification* in a successful IAFIS system. The reason for insisting on this point is that the relatively coarse bins implied by pattern-level classification impose exhorbitant computational expense on the matching component of IAFIS, to the extent that the single most promising avenue for improvement on conventional IAFIS is to introduce introduce and automate a finer level of classification than pattern-level classification. Therefore, in IAFIS as a whole, classification is so important that *there must be no permanent committment ot any particular level or method of classification.*

4. Summary of Study Recommendations and Conclusions

1. Due to the 1994 timetable, conventional IAFIS must proceed with minutiae-based matchers and pattern-level classification. Preparation for conventional IAFIS can be redirected only when the superiority of some competing automated method is fully demonstrated.

2. Conventional IAFIS is at substantial risk of becoming an expensive technical failure, as compared to the state of the art when IAFIS becomes available or soon therafter.

3. The IAFIS risk can be greatly reduced by an appropriate form of diversification: a new research track parallel to conventional IAFIS, together with new IAFIS requirements to ensure that successful research results can be incorporated at any time.

4. The most important problem and source of risk for IAFIS is the lack of automated methods for classification. Automating this task will require new research.

5. New research is also needed to eliminate the risk of stagnation in matching algorithms, and to automate the verification task.

6. There are many totally new approaches to automatic fingerprint processing, classification, matching and verification. These must be investigated since they may strongly affect AFIS price and performance. They include:

- Trainable neural networks
- Relaxation algorithms
- Scale space algorithms
- Examiner expertise and ways to use it

7. General-purpose hardware is insufficient for the first conventional IAFIS implementation of matching.

8. Parallel supercomputing will probably be required for both conventional IAFIS and for possible new methods which could challenge special purpose matchers.

9. The IAFIS system requirements should be altered to ensure openness in hardware, software, and especially in continual competition between fingerprint identification methods. To this end we recommend:

    9.1. The FBI must enforce modularity of these tasks: image processing, classification, matching and verification. Enforcing openness, the IAFIS design must allow alternative methods for each task to be installed at any time for extended testing or to actually replace the previous method. Most importantly, each competing contractor must make public their interfaces between these tasks, so that other competitors can subsequently challenge a successful method with an even better one.

9.2. Openness should be encouraged by being considered as an acceptable tradeoff for poorer initial demonstrated performance in evaluating IAFIS proposals. For example, finer-scale openness than the task level is optional but compensates for poorer initial performance.

9.3. The FBI should actively support competition between methods for fingerprint identification tasks, by supporting large-scale experimentation with promising new methods on its fingerprint data base and by conducting an annual review to determine which algorithms should actually be used in IAFIS during the coming year.

9.4 There must be no permanent commitment to any particular level or method of classification.

10. Further study of the skills displayed by experienced fingerprint examiners is needed; in-depth interviews with tech and latent examiners together with attempts to express their strategies procedurally would provide insight into algorithms to limit bin size.

11. The parallel IAFIS research track should include a substantial external research component (in addition to internal research) with an associated budget starting immediately and extending many years past IAFIS s planned installation and start-up. The following considerations are important:

11.1. There should be a public challenge fingerprint-pair database, along with publicly available source code to a matcher. There should be private full-scale database tests for algorithms that do relatively well on the public database.

11.2 Diversity is important; a variety of methods should be explored by academia and industry.

5. Conclusion

The Integrated Automated Fingerprint Identification System (IAFIS) is a *necessary but intrinsically risky* project. Using algorithms and technology that can be counted on because they currently exist, the project will be very expensive and not capable of handling a major escalation of the current workload. The investment in IAFIS could come to be seen as largely wasted if, as seems quite plausible, a relatively small amount of research could produce substantially improved automated methods, especially for classification. The improved methods could be much cheaper, more reliable and/or capable of handling a much greater workload and therefore entirely new applications. Missing these obvious opportunities, and thereby consigning IAFIS to early obsolescence, is the main source of intrinsic risk.

Fortunately there is a simple strategy available to greatly reduce these risks by an appropriate form of *diversificiation*: to invest not only in conventional IAFIS but also in a parallel *research track* that aims to apply recent developments in mathematics, engineering and computer science to the major fingerprint identification subtasks: image processing, classification, matching and verification. The research track by itself is at least as risky as conventional IAFIS, but the combination of the two investments are almost perfectly balanced in risk: when one fails, the other succeeds and vice versa. Success in the research track could have the additional benefits of greatly decreasing the hardware costs, or greatly enhancing the system capacity and extending areas of application such as latent print identification.

The research track cannot perform its function of greatly reducing IAFIS risk without altering the conventional IAFIS specifications to enforce continual *openness*, especially to newly discovered fingerprint algorithms. We have suggested how this may be done.

Appendix I. Establishing a Research Track

After our briefing of 13 September 1991, we were asked to provide a short outline of our suggestions for setting up a research track for the Bureau. The following includes our own opinions of how such a track could be established. It should be noted that these thoughts represent only a FIRST STEP in creating a research program. We see the entire research program as an on-going, evolutionary process, each research development enhancing procedures from the past, also interfacing with potential methods in the future. Also, this portion of our report is much more casually put together than the main body and is really just an illustration of how one might translate our list of recommendations and our Potential Applicability Table into an IAFIS research track; it could be done in many other ways too.

Due to the 1994 timetable, we are suggesting that the FBI begin immediately to seek both internal and external sources of research. If too much time is devoted toward the consideration of various research options, valuable time and results may be lost. It is important that the FBI begin its research efforts as soon as possible, perhaps using our report as a seed to start this new research track.

1. STARTING UP - INTERNAL AND EXTERNAL PROGRAMS

1.1. Research Areas and Tasks

We have determined four research major areas offering great potential for automatic fingerprint identification, as summarized in our Potential Applicability Table. In addition we feel that there should be a fifth category, labelled "other ", which can encompass important areas we may have missed - but not with overwhelming weight, or the beneficent guidance effects of our report will be nullified! So the five research areas are:

- Trainable neural networks
- Relaxation Algorithms
- Scale space algorithms
- Examiner expertise with ways to use it
- Other

In addition to the (now five) research areas, we have also identified four computational tasks which are at the core of IAFIS and into which IAFIS can be modularized, more or less:

- Image processing
- Classification
- Matching
- Verification

These are all to be understood as specialized versions of image processing, classification etc. that are optimized for fingerprint images, rather than the corresponding tasks in a general computer vision system.

1.2. Internal Program: Examiner Expertise

The examiner expertise area, by its very nature, suggests the need and desire for an "internal" research program, examining the insights, skills and procedures exhibited by experienced tech and latent examiners. This program would need two principal managers.

One manager should be an experienced examiner. This individual would construct a program devoted to utilizing in-house sources to collect and evaluate information related to the area, as we have described.

In order to utilize the research from the in-house program, we suggest that the Bureau hire an expert in an area related to Expert System Design and Integration, Knowledge Engineering and Rule-based systems. This manager would be responsible for working closely with the Examiner program manager. Together, this team would seek to create methods by which examiner expertise could be applied to the design of a front-end automated process for fingerprint identification. We feel that a first step in this effort should focus on the four categories described in our POTENTIAL APPLICABILITY TABLE: Examiner Debriefing, Hand-Designed Codes, Expert Systems, and Expert System/Neural Network Hybrid Systems.

1.3. New Mathematical and Engineering Directions: Internal and External Program

The first three research areas will require the mathematical expertise of at least one Ph.D. This individual should have a background in Mathematics (pure or applied), Neural Networks and Computer Science. He or she should be capable of designing and directing a program to do the following:

- Seek outside research proposals.

- Evaluate proposals and make recommendations for support of those with greatest potential.

- Evaluate results of funded programs and choosemost effective ones for implementation.

- Design programs to integrate new results with current IAFIS program.

- Continually update and evaluate entire research program, establishing procedures to carry the entire research effort well into 21st century.

- Hire and direct in-house staff to perform research in the same general directions as the external research program, both to ensure technical competence at the Bureau and to integrate various research advances.

2. SUGGESTIONS FOR SEEKING PROPOSALS WHICH EXPLORE THE POTENTIAL APPLICABILITY TABLE

A major contribution of our own research study was the determination of the four major research categories as outlined above. However, in order to design a truly effective research program we feel that a "fifth" area for other possible methods should also be considered, called "OTHER". This category is meant to include any viable mathematical method not already considered.

In addition, another important feature of our approach was the breakdown of the entire fingerprint problem with respect to the four major tasks: IMAGE PROCESSING, CLASSIFICATION, MATCHING, AND VERIFICATION. As indicated in the Potential Applicability Table, almost no method appears to have great potential for every one of the four facets of the problem. Thus, we maintain that the five research areas can be incorporated with the four tasks to present "twenty possible research blocks". We make the following recommendations for seeking proposals directed towards one or more of the "twenty research blocks":

- Proposals would present a research effort directed towards at least one of the twenty possible research blocks (e. g. scale-space algorithms and matching).

- Proposals would not be limited to just one of the twenty blocks; a potential research effort could analyze a particular mathematical method as it addresses two or more of the tasks; likewise one should also allow for proposals which consider more than one method as it relates to a specific task.

- Proposals for research could also address computational issues raised in the other columns of our Potential Applicability Table: Trainability, Scalability to large images and data bases, incorporation of Model-Based Algorithms, Potential for Integration with Cheap Chips, and nontrivial Similarity Measures. Proposers could be encouraged to present an analysis for how their methods handle these issues.

- Proposals would present suggestions for integrating the method into the identification process, suggesting research for potential interfaces.

- Proposals would also offer suggestions for the types and kinds of hardware that would be required if their method would be implemented.

- The FBI would enforce openness in their call for proposals and the research to follow.

- Coverage: The FBI needs at least one project in each of the five research areas, preferably distributed in a uniformly balanced way. Also, the FBI needs at least two competing research projects in each task area.

3. SUMMARY OF KEY SUGGESTIONS FOR NEW RESEARCH TRACK

Under these suggestions:

1. Research program would be initiated as soon as possible.

2. Research program would be directed towards the modularity of the four specific tasks: Image Processing, Classification, Matching and Verification.

3. Proposals would be analyzed according to task as well as method, addressing at least one of the twenty possible research blocks: four tasks and five research areas, including "other".

4. Proposals would be required to have high marks in the "openness" issue.

5. Proposers would be required to devote part of research program towards development of appropriate interfaces.

6. The FBI would seek coverage, within the research track, of five new research areas (four of which we have discussed plus a catchall category); and also several competing methods for each of the four main IAFIS tasks we have listed.

7. FBI would establish an "evolutionary" research program with an annual evaluation process to determine effective methods under consideration and to continually look towards future areas of potential methods.

We would like to reiterate the provisional nature of these suggestions, in contrast to the main body of our report.

References

1. According to Myra Prelle of MITRE, reporting on a MITRE study, in conversation with E. Mjolsness, 2 July 1991.

2. For example, in MITRE s "System Requirements Definition for the Integrated Automated Fingerprint Identification System", MTR-91W00069, draft of May 1991 (hereinafter referred to as the MITRE proposal), page 6-16, automated classification appears only as an alternative requirement 6.2.1-1a to the main requirement 6.2.1-1 for workstations that support manual classification. The story is the same for verification on page 6-19.

3. R. T. Moore, National Bureau of Standards letterhead memo to Walt Johanningsmeier, August 30 1988. A three-page essay on the computational workload for minutia-based matchers, assuming pattern-level classification for 10-print cards.

4. Dr. Larry Smarr, presentation and discussion in a meeting with FBI and MITRE representatives as well as E. Mjolsness at the National Center for Supercomputing Applications (L. Smarr, director), 2 July 1991.

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14. Evidence for convergence of relaxation networks, implemented in analog VLSI, in 10 to 100 microseconds is provided by two independent reports presented at the International Joint Conference on Neural Networks (IJCNN) 1991. The two investigators were Paul Muller, reporting on a set of building block chips, and Joshua Alspector reporting on his annealing chip running in deterministic mode.

15. Y. LeCun, B. Boser, J. S. Denker, D. Henderson, R. E. Howard, W. Hubbard, and L. D. Jackel, "Backpropagation Applied to Handwritten Zip Code Recognition", Neural Computation, v.1 no. 4,1989.

16. Pierre Baldi, in a telephone conversation with E. Mjolsness, 19 July 1991.

17. For a mathematical review see Gilbert Strang, "Wavelets and Dilation Equations: A Brief Introduction", SIAM Review, v. 31 no 4, December 1989.

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26. The MITRE proposal apparently makes only one estimate of the number of matchers required for conventional IAFIS. It is hidden away in subsection 9.2.6, "Reliability", of section 9, "Evaluation of Alternative Concepts", where we read that "In the case of fingerprint matchers, if the current state-of-the-art architecture does not change by the time that IAFIS is procured, the FBI may be acquiring hundreds of devices to perform this function." No cost estimate is attached.

27. For example, on September 12 1991, the day before our briefing was presented at FBI headquarters, there appeared in the business section of the New York Times an article headlined "New IBM Line is Open - Products Can Work With Other Brands" which heralded the capitulation of one of the most powerful holdouts against open systems (IBM) to the new, more comptetitive way of organizing computer systems of all sizes.

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30. The MITRE Corporation, "Systems Requirements Definition for the Integrated Automated Fingerprint Identificiation System", MTR-91W00069, Draft of May 1991.