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An Overview of the Science of Fingerprints

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ABSTRACT

Abstract (English)

This paper contains an overview of the science of fingerprints. It is designed for novices, or as a tool for experts to use when educating general audiences. The author has created a series of overheads, exercises and other materials that can be used in conjunction with this work. In addition, a more printer friendly version is available. You may request these materials by contacting the author.

Abstract (Italian, Italiano)

Questo articolo presenta una panoramica sulla scienza delle impronte digitali. E' disegnato per principianti, o come strumento didattico che esperti possono usare davanti ad una platea generale. L'autore ha creato una serie di lucidi, esercizi ed altro materiale che può essere usato assieme a questo lavoro. E' inoltre disponibile una versione dell'articolo più adatta alla stampa. E' possibile richiedere il materiale contattando l'autore.

Abstract (German, Deutsch)

Dieses Papier gibt einen Überblick über die Wissenschaft der Fingerabdrücke. Es richtet sich vornehmlich an Anfänger, kann aber auch von Experten als Lehrmaterial verwandt werden. Der Autor hat Folien, Uebungsaufgaben und zusätzliche Lehrmaterialien zusammengestellt, die zusammen mit diesem Papier benutzt werden können. Eine druckerfreundliche Version dieses Papiers ist ebenfalls erhältlich. Diese Materialien können direkt vom Autor angefordert werden.

Abstract (Romanian, Romana)

Acest articol contine o prezentare generala a stiintei amprentelor digitale. Este proiectat atat pentru incepatori, cat si ca o unealta pentru experti, pentru educarea unui public larg. Autorul a creat o serie de prezentari, exercitii si alte materiale care pot fi folosite impreuna cu acest articol. O varianta pentru imprimanta este de asemenea disponibila. Puteti cere aceste materiale contactandu-l pe autor.

Abstract (Portuguese, Português)

Este artigo apresenta uma introdução à ciência das impressões digitais. O artigo é direcionado a nao-profissionais ou a profissionais que desejam utilizá-lo para fins educacionais. O autor criou uma série de transparências, exercícios e outros materiais didáticos que podem ser utilizados em conjunto com o artigo. Além disso, uma versão deste artigo existe em formato pronto para ser impresso. Todo o material disponível pode ser obtido através do autor.

Abstract (Spanish, Español)

Este articulo contiene un repaso de los principales resultados en la ciencia de las huellas digitales. Esta escrito pensando en una audiencia inexperta y puede usarse como base en un curso de caracter general. El autor ha elaborado transparencias, ejercicios y otros materiales que se pueden usar junto con este articulo. Ademas, una version del articulo mejor editada tambien esta disponible. Todo este material se puede conseguir contactando al autor.

Introduction

The early history of fingerprints is shrouded in conjecture. It has been suggested that thumbprints on Babylonian clay tablets and ancient Chinese clay seals were deliberately placed there as identifying marks. Stone carvings, dated 3,000 BC, outside a burial chamber called Newgrange in Ireland are speculated to have been inspired by fingerprint patterns. For this work however, we will concentrate on the scientific history of fingerprints, which revolves around two discoveries, firstly, fingerprints remain unchanged over an individuals lifetime, and secondly, all fingerprints are unique.

These discoveries are of limited use without the invention of efficient methods to index fingerprints. This will be the subject of the second half of this work.



Figure 1: Sir William Herschel (1833-1917)

The first individual to use fingerprints on a large scale was Sir William Herschel [6], a British government official living in India during the second half of the nineteenth century. He made the natives place their fingerprints (in some cases, their entire handprint) on legal documents. At first Herschel's idea was simply that the solemn ceremony of physical contact with an official document might discourage attempts of cheating. Later however, he realized that fingerprints could be a

general method of identification for both criminal and civil affairs. He introduced fingerprint identification on a wide scale in his province in India, but failed to attract interest back in England.



Figure 2: Henry Faulds (1843-1930)

At approximately the same time, Henry Faulds, a Scottish doctor living in Japan began collecting fingerprints. By chance, he was asked to help investigate a crime in which very clear fingerprints in soot were left at a crime scene. He was able to convince the authorities that their number one suspect could not have left the prints, but a minor suspect must have left the prints. This was the first time a crime was solved based on fingerprint evidence. Faulds wrote a letter on the subject to the journal *Nature*, and more importantly, wrote a letter to Charles Darwin outlining his discoveries. Darwin at this time (1880) felt that he was too old to get involved, but passed the letter on to his cousin, the brilliant anthropologist Sir Francis Galton.

Sir Francis Galton's contribution [4] (detailed later) was to firmly establish that fingerprints are unique, using a simple yet elegant mathematical argument. With the permanence of fingerprints already established by Herschel, the only problem remaining before fingerprints could be use for criminal identification was the design of an efficient method of indexing the prints. Sir Edward Henry and others solved this problem, their contributions will be discussed later in the relevant sections.

Class characteristics of fingerprints



Figure 3: Johannes Purkinje (1787-1869)

The Czech physiologist and anatomist, Johannes Purkinje [2] first recognized the fact that all fingerprints can be grouped into a small number of classes. In his doctoral thesis he identified nine different patterns, including the Arch, the Tented Arch, the Loop and six different types of Whorls. Modern fingerprint experts still consider the first three to be distinct classes but usually combine all the whorls into a single class.

Below I have illustrated the four main types of fingerprints and provided informal definitions.

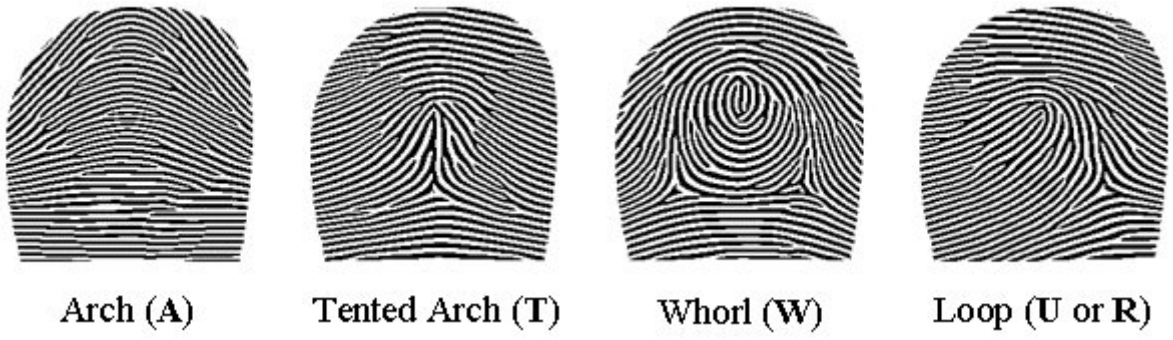


Figure 4: The four main classes of fingerprints

An Arch fingerprint has ridges that enter from one side, rise to a slight bump and exit out the opposite side from which they entered.

A Tented Arch fingerprint is similar to the (plain) Arch except that at least one ridge stands at an angle of 45 degrees or more.

A Whorl fingerprint contains at least one ridge that makes a complete 360-degree circuit around the center of the print.

A Loop fingerprint has one or more ridges enter from one side, and recurve and exit the same side they entered (Loops can be further subdivided, as discussed below).

Classes of fingerprints occur with different frequencies, with Arches being fairly rare and Loops being relatively common. The pie chart to the right shows the approximate distribution of classes. The exact distribution varies (slightly) for different races and different fingers.

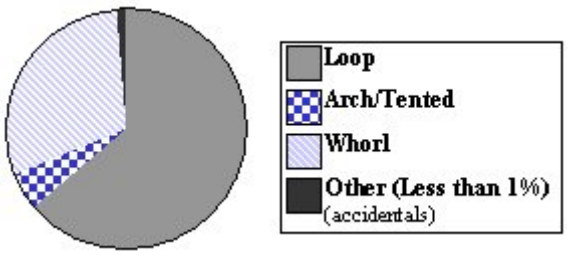


Figure 5: Distribution of Classes

Note that Loops are the only asymmetric fingerprints (ignoring the fact that Whorls can have clockwise and anti clockwise spirals). Loops that have ridges that enter and exit from the left side are called Left Loops and Loops that have ridges that enter and exit from the right side are called Right Loops. If we know which hand a Loop print came from (left vs. right) we can further subdivide the loop into two classes as shown below.

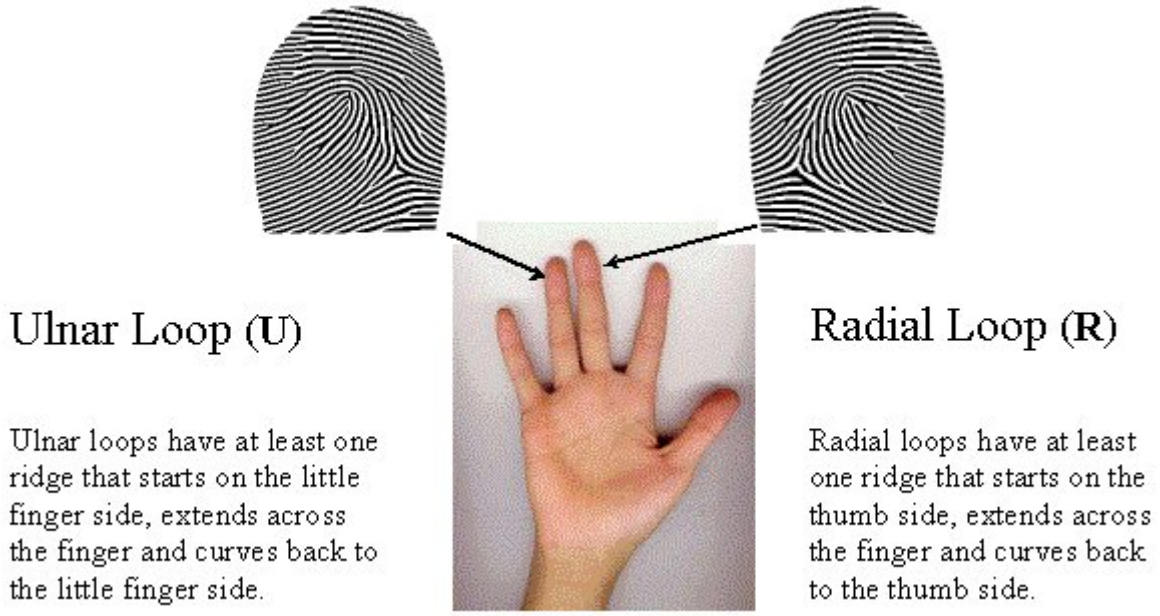


Figure 6: Ulnar Loop Vs. Radial Loop

The four pattern types are known as class characteristics., Although they are useful for filing fingerprints, they are not sufficient for identifying an individual. To do this, we must consider minutia.

Minutia: Individual characteristics of fingerprints

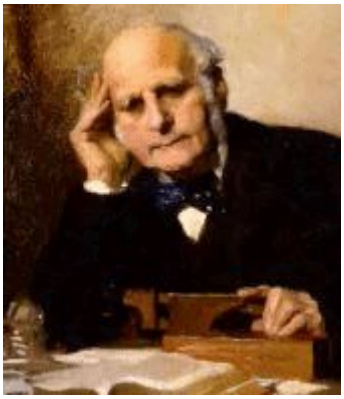


Figure 7: Sir Francis Galton (1822-1911)

Minutia means *small details*. In the context of fingerprints minutia refers to various ways that the ridges in a fingerprint can be discontinuous. For example, a ridge can suddenly come to an end, rather like a road might come to a dead end. Such a feature is naturally called a *Ridge Ending*. Another example with an analogy to roadways is a ridge that divides into two ridges, just like a road divides at a three-way intersection. This feature is called a *Bifurcation*. Sir Francis Galton (1822-1911) was the first person to categorize minutia and to observe that they remain unchanged over an individuals lifetime. Minutia are sometimes called "Galton Details" in his honor.

The image below identifies four kinds of minutia. Some fingerprint experts identify up to 19 different types. However, most fingerprint experts consider only two kinds: bifurcations and ridge endings. There are two justifications for this simplification.

1) Bifurcations and ridge endings account for the vast majority of all minutia.

2) All other minutia can be made up of combinations of bifurcations and ridge endings. For example an *Enclosure* can be viewed as two bifurcations facing each other, and an Island can be viewed as two ridge endings, a very short distance apart.

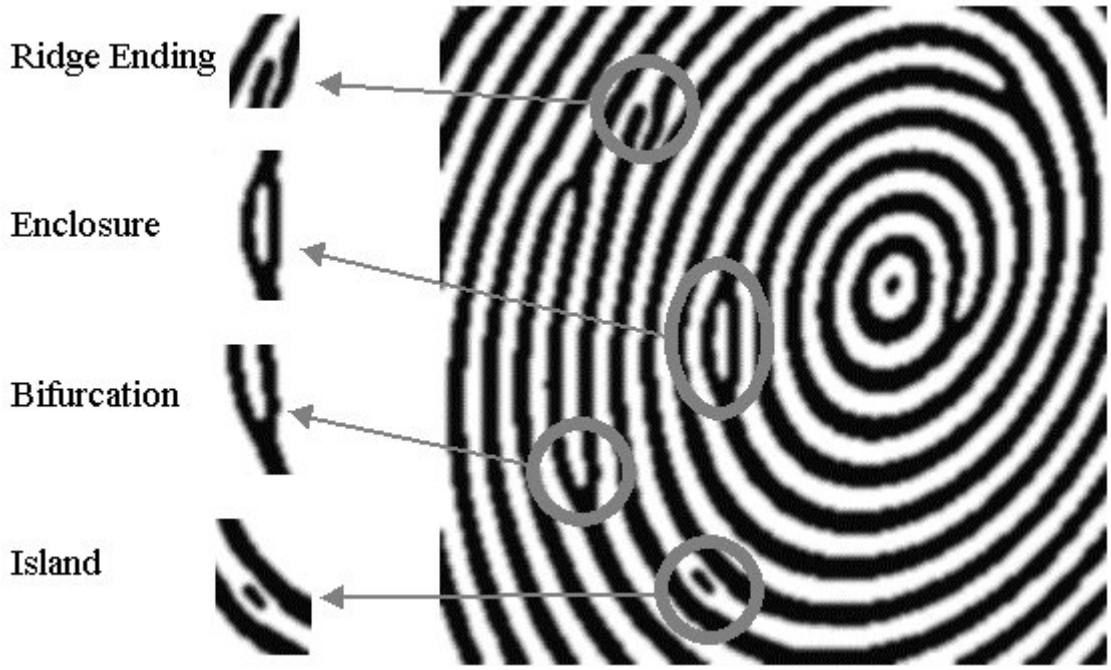


Figure 8: Four kinds of minutia

Before using fingerprints (or any other body measurement) for identification we must first establish two facts about them: their permanence and their uniqueness.

Permanence (in this context) means that fingerprints do not change over time. This fact can be established empirically. For example, the author had his right index finger fingerprinted in 1987 for his resident alien card. Below is a copy of that print together with a recent fingerprint from the same digit.



Figure 9: Permanence of fingerprints.

As you can see, even after 13 years the prints appear identical (Later, you will learn more formal skills in fingerprint comparison). Several of the fingerprint pioneers performed similar experiments. For example Sir William Herschel took his prints in 1860 and again in 1890, and found them unchanged. Researchers have taken fingerprints of newborn infants and retaken them

when the child reaches adulthood. The prints obviously enlarge over time but the patterns do not change.

It is now known that fingerprints form in the womb at around 5 months and remain constant even after death. In fact, fingerprints have been successfully taken from well-preserved mummies more than 2,000 years after their death.

Uniqueness is more difficult to establish than permanence. Empirically, it can be noted that no one has ever found identical prints. Identical twins seem like the most likely candidates for identical prints, so since the days of the early fingerprint pioneers, thousands of twin's fingerprints have been examined, and no one has found a matching pair.

Although this empirical evidence is useful, we can give a stronger argument based on statistics. Sir Francis Galton published a book entitled *Fingerprints* in 1892. In this book, Galton provided a (very conservative) estimate of the number of possible fingerprints. He showed that there are at least 64 billion fingerprints possible. Given that this is larger than the number of people alive, we reasonably state that fingerprints are unique.

Given that we have established the permanence and uniqueness of fingerprints we are ready to learn how they can be use to solve two problems, authentication and identification. First, let us define these problems.

Authentication*: Is this person really who they claim to be?* This problem occurs in law enforcement in the following context. Most legal systems in the world hand out sentences to offenders based on their previous records. For example, in California, a first offence of a felony might result in a prison term of as little as one year. But a third conviction will result in a 25-year mandatory sentence (Penal Code 667). Suppose you have two convictions behind you and you are captured after a bank holdup, would you give authorities your real name? It would be in your interest to lie about who you are, if possible. You would be better off serving one year under a false name than 25 years under your real name. This is an example of the authentication problem. If a suspect claims to be "John Smith", the fingerprints of John Smith are retrieved and compared to the suspect. If they match; all is well, if they don't match, further action is taken to establish the true identify of the suspect.

Identification: *Who is this person?* This problem differs from authentication in that with the authentication problem there is some claim as to identity that must be confirmed or denied. In contrast with the identification problem, there is no claim of identity. The problem is to find the identity of an individual out of large set of possibilities. This problem commonly occurs in law enforcement in two contexts. First, fingerprints may have been left at the scene of a crime, and naturally, we would like to know who left those prints. Secondly, a body may be discovered with no identifying clothing, tattoos, scars, etc. We would like to know the identity of the body.

Note that the problems are related, but differ in one important aspect. Authentication simply requires retrieving a set of prints and checking to see if they match the individuals claim of identity. In contrast, identification requires searching through a large set of records to find a match. Identification is therefore considered a much more difficult problem.



Figure 10: Do these two prints match?.

To solve the authentication problem we can simply compare an individuals fingerprints with his prints on file. Great care must be taken during this process not to be distracted by superficial differences. For example, the apparent thickness of the ridges can differ greatly depending on the ink used and the amount of pressure applied.

Prints are compared by finding matching minutiae in the two prints under consideration. In order for two prints to be considered as emanating from a single individual, all the minutiae found in one must be also found in the other. The minutiae must match in type, relative location and orientation. There are some important caveats however.

It is possible that the relative position of matching minutia might appear slightly shifted because the finger "smeared" when the prints were taken.

It is possible that a minutia may have been obscured by over or under inking, by dirty ink, or by scarring.

A single unexplained difference between the two prints is enough to guarantee that they come from difference sources. But how many agreeing points must we have before we can guarantee that the prints come from the same source? This has been the subject of some debate. Most European courts require 16 minutiae, a few countries require more. In America, the testimony of a fingerprint expert is sufficient to legally establish a match, regardless of the number of matching minutiae, although defense lawyers will often hammer away at an expert who introduces evidence with fewer than 10 matching points.

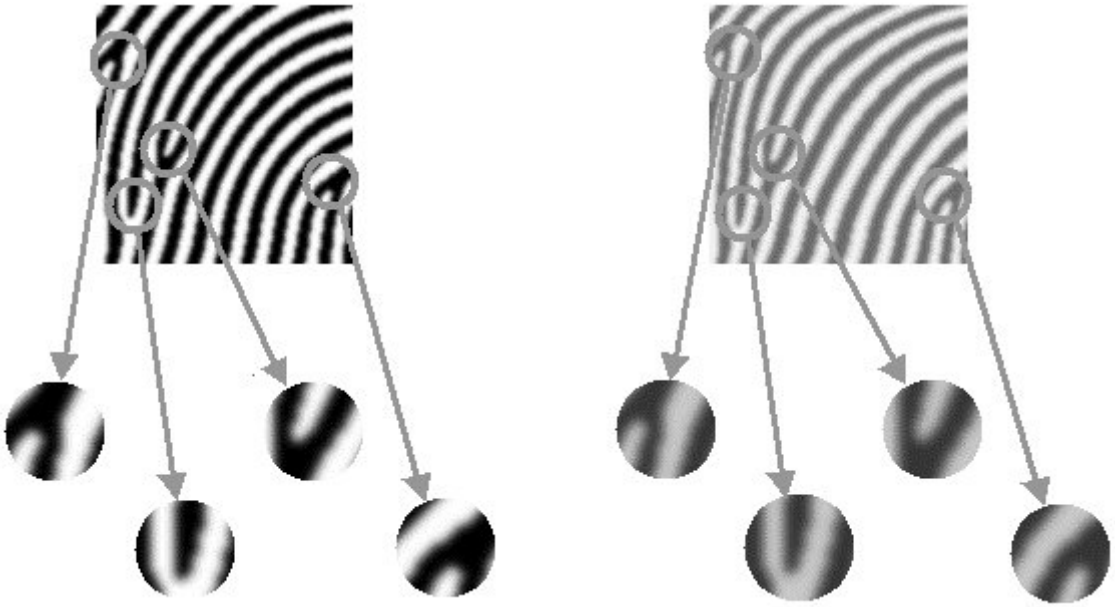


Figure 11: The type, relative location and orientation of all minutiae match and there are no unexplained differences. Therefore these two prints can be considered a match.

To solve the fingerprint identification problem, we could simply search through our entire fingerprint collection, looking for a match to the mystery print. The problem is that a fingerprint database might contain millions of records. Even the fastest expert might take months to search through a million records.

To solve the problem, the fingerprints must be *indexed*. Consider the problem of locating a particular song in a music store. The store might sell 100,000 titles, but it is still easy to find a desired song (or to discover that it is not in stock). The CDs are first organized into categories, and are further organized within the categories by alphabetical order.

Imagine we are looking for the Beatles song "Yesterday". We can quickly go to the Rock/Pop category, find the CDs beginning with "B", then find the CDs by the Beatles. Once we find the bin containing the Beatles CDs, we will have to do a manual search through all 10 of their records if we don't know which record contains the song "Yesterday". However, searching through 10 items is a lot faster than searching through 100,000!

It is relatively easy to design an index for items that have a name that can be alphabetized, or an identifying number, that can be sorted, but how are we to index fingerprints?

The Henry Classification System

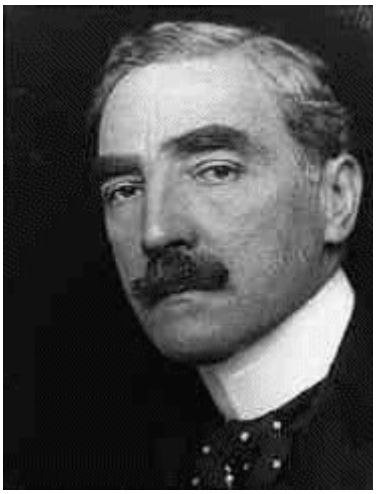


Figure 12 : Sir Edward Henry (1850-1931)

Sir Edward Henry solved the fingerprint-indexing problem with an ingenious solution in 1897 [5]. Scotland Yard adopted the Henry-System in 1901. Since then, the system has been adopted by virtually every country in the world (with minor regional variations).

Henry was a high-ranking official in India during the nineteenth century. He was responsible for the government payroll, paying the natives who worked on the roads and railways. When Henry took over the position, there was a high rate of fraud. Some individuals would claim two or more paychecks under different names. If a worker died, his family would often hide the body and continue to claim his paycheck for years.

Literacy was low among the workers, so using signature verification was not a possible solution. Photography was in its infancy and very expensive, so identification cards were not a possibility. Another Englishman living in India, Sir William Herschel, had already solved the *authentication* problem by using fingerprints (again, the motivation was fraud prevention). But it was the Henry Classification system which solved the *identification* problem.

The Henry classification system works by examining the pattern types on all ten fingers and producing a label. The fingerprint record is then filed under this label. There are 1,024 possible labels under the system, so when it is necessary to locate a record, only 1/1,024th (on average) of the entire collection must be examined.



Figure 13: The classes of the authors fingers

The first step is to identify the class of each finger. Particular care must be taken to associate the correct class with the correct digit.

For example, the author has an Ulnar Loop (**U**) on his right little finger, a Whorl (**W**) on his right ring finger, and Arch (**A**) on his right middle finger, an Ulnar Loop (**U**) on his right index finger as shown to the right.

(Note: There are many extensions of the Henry System that consider classes other than Whorls, for simplicity we are ignoring them in this work. See [3] for a high level view of some extensions and alternative schemes).

The classes are divided into two types: those that have a numerical value, and those that do not. In particular Whorls have a numeric value; all other types do not. The value associated with a Whorl depends on its position. The chart below lists the values.

The Henry Classification Table

(1) R. Thumb 16	**(2) R. Index 16**	**(3) R. Middle 8**	**(4) R. Ring 8**	**(5) R. Little 4**
(6) L. Thumb **4**	(7) L. Index **2**	(8) L. Middle **2**	(9) L. Ring **1**	(10) L. Little **1**

So, for the author, who has Whorls on the ring finger of both hands, the values illustrated below will be used as the basis of his Henry classification.

The Henry Classification Table with the authors Whorl classification highlighted.

(1) R. Thumb	**(2) R. Index**	**(3) R. Middle**	**(4) R. Ring 8**	**(5) R. Little**
(6) L. Thumb	(7) L. Index	(8) L. Middle	(9) L. Ring **1**	(10) L. Little

The next step is to form a "fraction" based on the following two rules:

The sum of the values of the white squares that contain a Whorl (plus one) is the numerator.

The sum of the values of the dark squares that contain a Whorl (plus one) is the denominator.

So the author's Henry classification is (**8** + 1)/(**1** + 1) = 9/2 (read as "nine over two"). Note that this label is not really a fraction. Therefore, the labels 8/4 and 4/2 are distinct. You **cannot** simplify a label by canceling above and below the bar.

Single Print Classification



Figure 14: Superintendent Fredrick Cherrill (1892-1964).

The Henry classification system has been used successfully for over one hundred years in virtually every county in the world. However, it does have an important limitation. It can only be used when the pattern types of all ten digits are known. It is extremely unlikely that a suspect would leave all ten prints at a crime scene. Given this fact, several attempts at single print classification systems have been made. The most successful of these was invented by Scotland Yard fingerprint experts Harry Battley and Superintendent Fredrick Cherrill [1]. Their system is elegant and ingenious, but requires extensive training. We will therefore confine ourselves to learning just one part of their system, ridge counting.

We must first begin by defining two terms, *core* and *delta*. The exact definitions of these terms are rather complicated, so we will content ourselves with informal definitions and a sample illustration.

We will consider only the Loop pattern. The definitions for Whorl are similar, Arches and Tented Arches don't have cores or deltas.

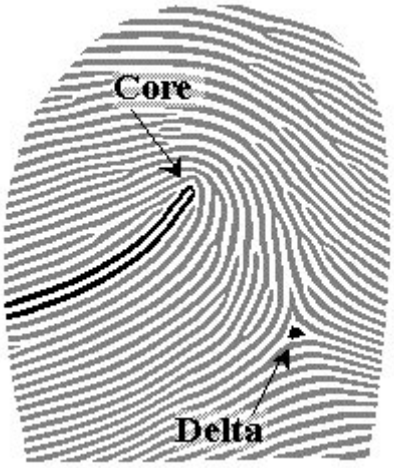


Figure 15: An illustration of a Core and Delta.

A Loop is defined by having at least one ridge that enters the print and recurves back exiting the print on the same side. The top of the innermost recurving ridge is defined as the *core*.

The other side of a Loop contains ridges that enter the print and meet the recurving ridges. Some of these rise above, and some fall below the loop. The point where they diverge that is closest to the recurving ridges is the *delta,* (there is often a small island at this point).

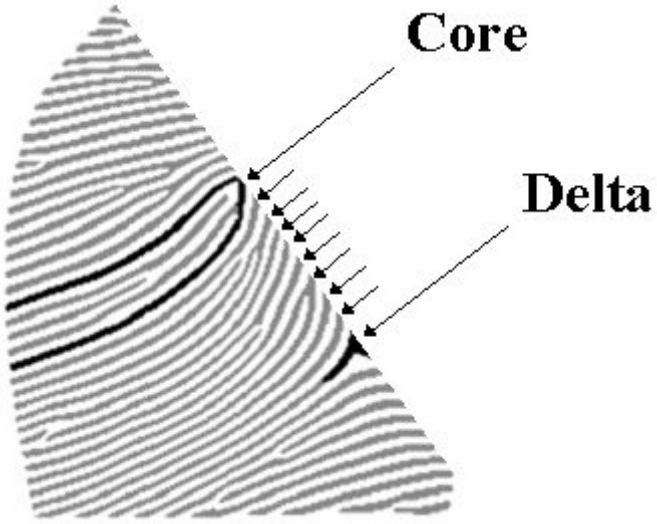


Figure 16: A fingerprint with a ridge count of 8.

We can draw a line from the core to the delta as shown in the figure to the right. The line crosses over some countable number of ridges. There must be as least one and can be as many as thirty or more intervening ridges. This number is known as a ridge count and can be used to index single prints. Note that there is a small possibility of two individuals arriving at different counts on the same print, because the counting line might pass close to bifurcations or to ridge endings. Therefore a fingerprint expert who is searching for a 8 count print will usually "bracket" her search by also examining the 7 and the 9 count index.

Once a ridge count is obtained, the fingerprint examiner will make a guess to which finger the print came from. For example, a print from a gun's trigger is almost certainly from an index finger, and if there were palm impressions on the right side handle, this would suggest that the print on the trigger is also from the right hand.

There are other well know heuristics for guessing the correct digit on door handles, credit cards, steering wheels etc.

Finally, individual prints are often indexed by the type of crime (This is usually only done for crimes with a high recidivism rate, like burglary, arson etc).

Crime Type	Ridge Count							
Burglary	less than 5	5	6	7	**8**	9	10	more than 10
Home Invasion	less than 5	5	6	7	8	9	10	more than 10
Arson	less than 5	5	6	7	8	9	10	more than 10

Imagine the cells in the table above correspond to bins containing the prints of known criminals. If the print shown in Figure 16 were found at a burglary, a fingerprint examiner would first look in the bin indicated by the dark blue cell. If a matching print is not found she would then bracket her search and look in the two bins corresponding to lighter blue cells. Finally if that did not yield a match she might look in the bins corresponding to the yellow cells, given that criminals sometimes change their *Modus Operandi* (M.O.).

Some interesting related links

THE HISTORY OF FINGERPRINTING IN CRIMINAL IDENTIFICATION AND THE LAUNCH OF FORENSIC SCIENCE

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5. Henry, Edward R. Sir.(1974). Classification and Uses of Finger Prints. New York: AMS.
6. Herschel, William J.(1880). Skin Furrows of the Hand. Nature. 76.

Note by the Editor: This paper was rated as the best paper of this issue. Subsequently it was cited by many authors in their own papers. Two examples currently on the web are:

Die verschiedenen technischen Möglichkeiten zur Erfassung von Fingerabdrücken by Birke Reinhard

Fingerabdrücke von Zwillingen ("Twin Test") by Florian Bauer