Fingerprint Recognition

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May 30, 2024

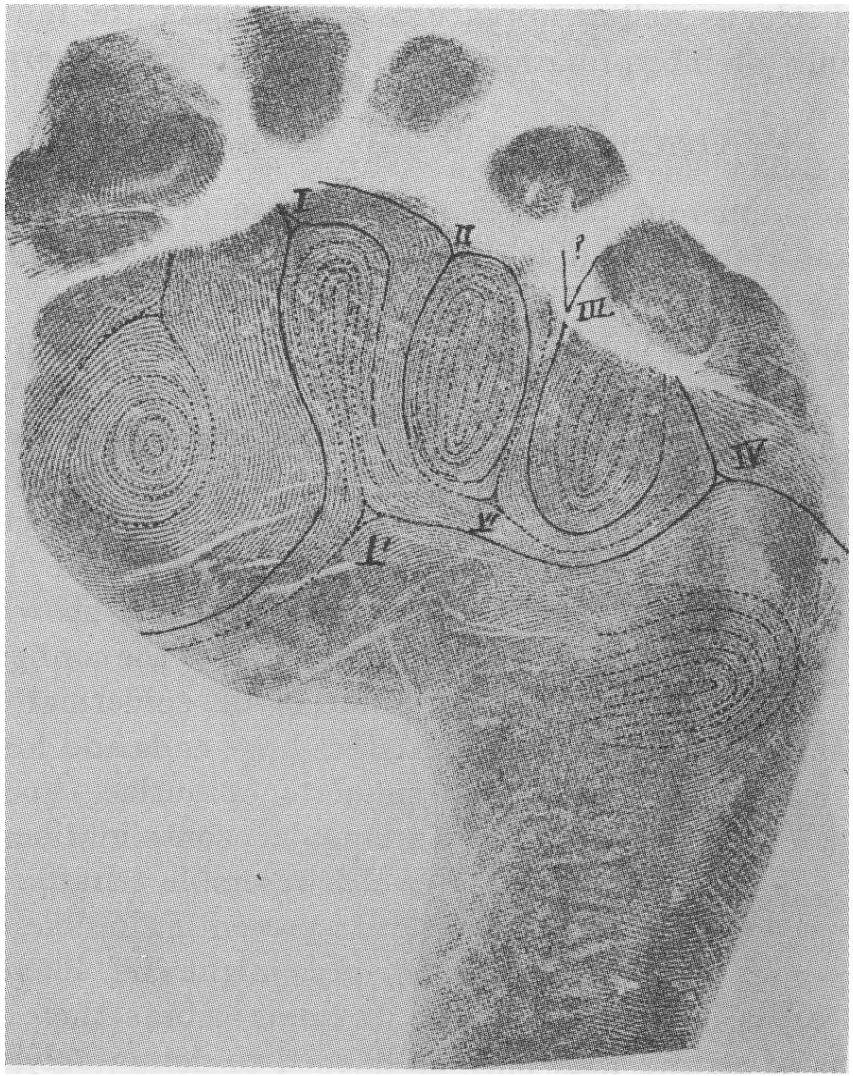
http://biometrics.cse.msu.edu/

Mobile Unlock and Payment

~1.17 billion smartphones shipped in 2023; iPhone 5S popularized fingerprint

https://www.statista.com/statistics/271491/worldwide-shipments-of-smartphones-since-2009/

Friction Ridge Patterns

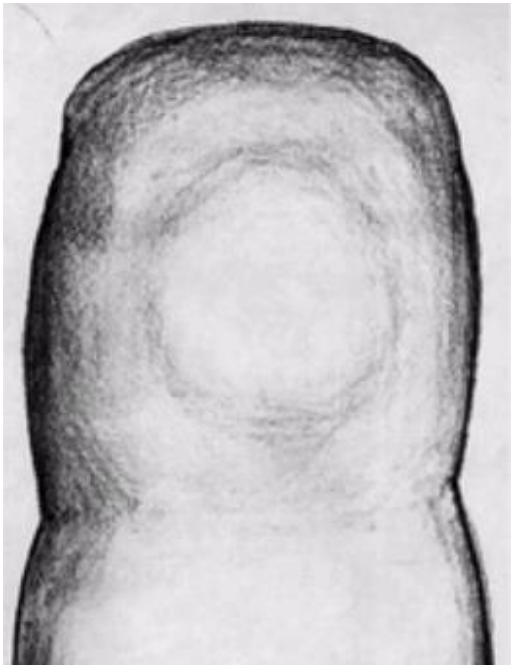


Cumins and Midlo, Finger Prints, Palms and Soles, Dover, 1961

Dermatoglyphics: Derma (skin) + glyphe (carve): study of ridged patterns

Fingerprint Formation

- Ridge formation starts at 1 or 2 focal points and spreads over the fingertip
- Localized ridge units merge to form ridges at ~10.5 weeks of gestational age
- Fingerprints possess genotype & phenotype properties

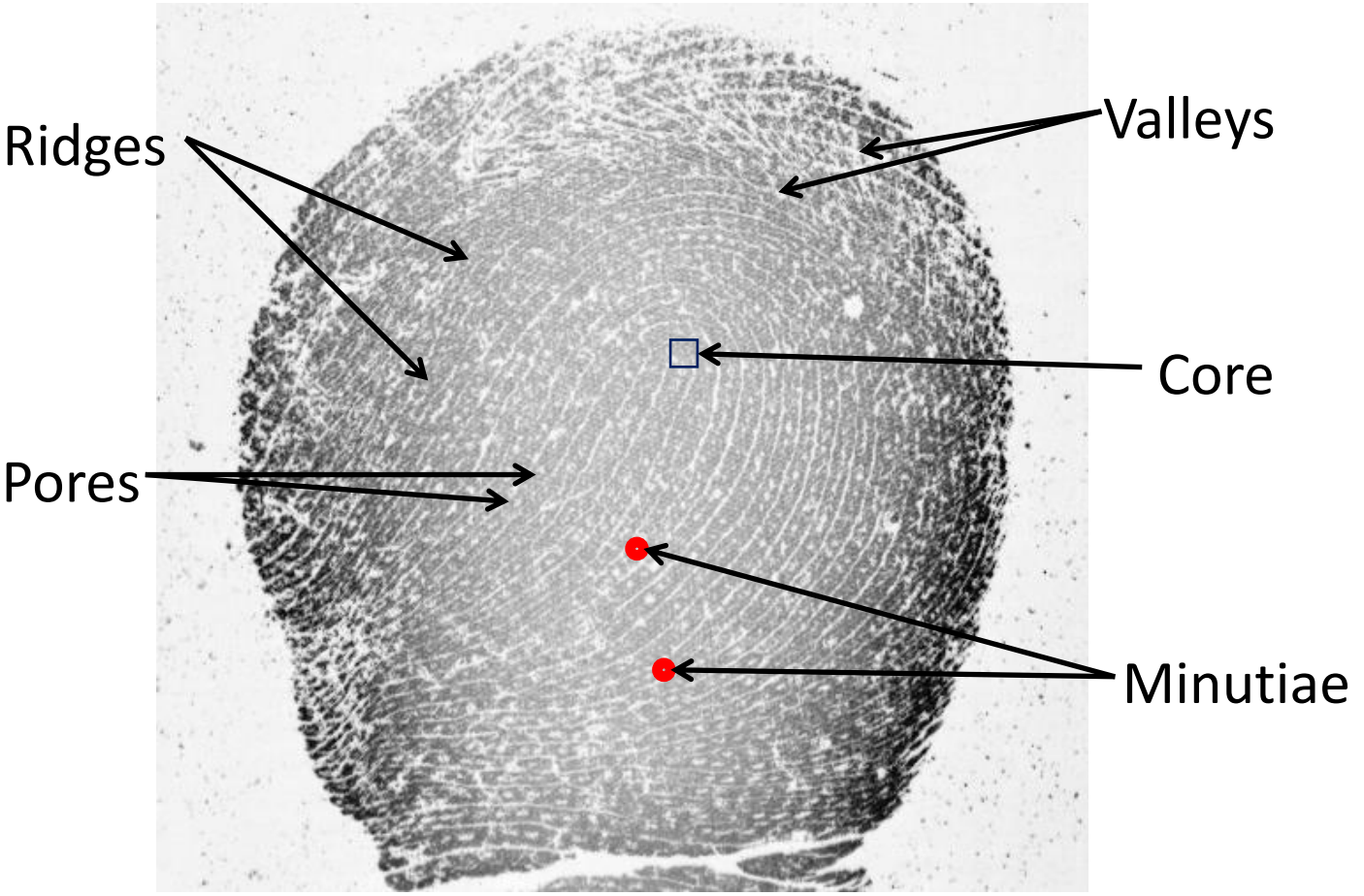


L. S. Penrose and P. T. Ohara. The development of the epidermal ridges. *Journal of Medical Genetics*, 1973

M. Okajima. Development of dermal ridges in the fetus. *Journal of Medical Genetics*, 1975

Newborns Have Fingerprints!

6-hour old baby



Fingerprint formation starts during the 10th week of gestation

Jain, Arora, Cao, Best-Rowden, Bhatnagar, "Fingerprint Recognition of Young Children", IEEE Trans IFS, 2017

Characteristics of Fingerprints

- Ridge characteristics are unique
- Ridge configurations are permanent
- Configuration types can be indexed
- 81 billion unique fingerprints (8.1bn x 10)

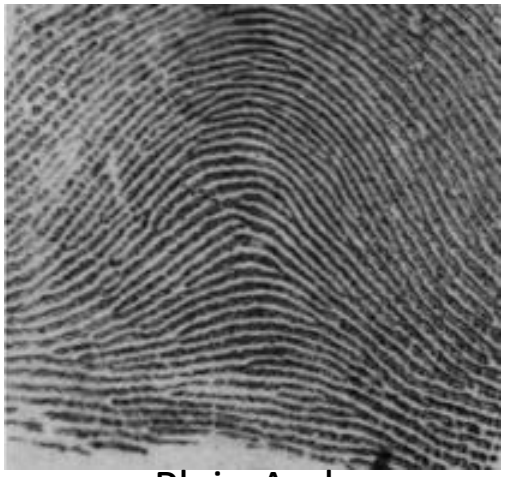
Identical twins have different fingerprints

"fingerprint" is associated with "uniqueness"

- S. Yoon and A. K. Jain, "Longitudinal Study of Fingerprint Recognition", *Proc. National Academy of Sciences (PNAS)*, July 2015.
- S. Pankanti, S. Prabhakar, and A. K. Jain, "On the Individuality of Fingerprints", *IEEE Trans. Pattern Analysis and Machine Intelligence*, 2002
- A. K. Jain, S. Prabhakar, and S. Pankanti, "On The Similarity of Identical Twin Fingerprints", *Pattern Recognition*, 2002.

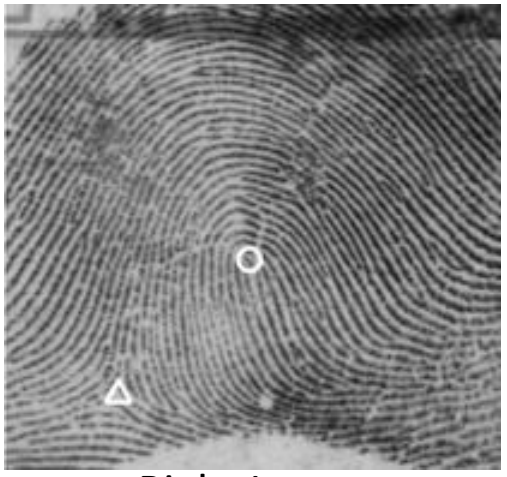
Fingerprint Types

6 major classes based on singular points (core & delta); loops and whorls account for 95% of fingerprints



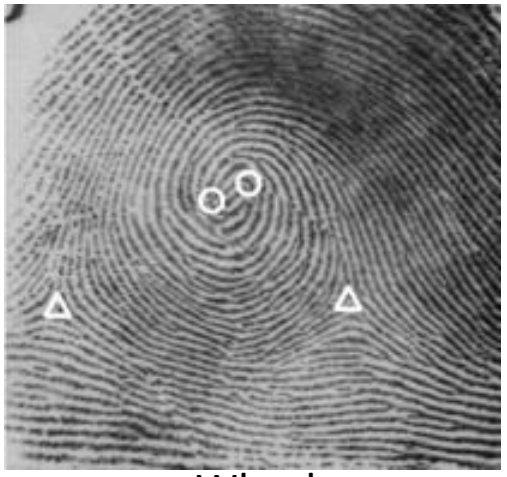
Plain Arch

Left Loop

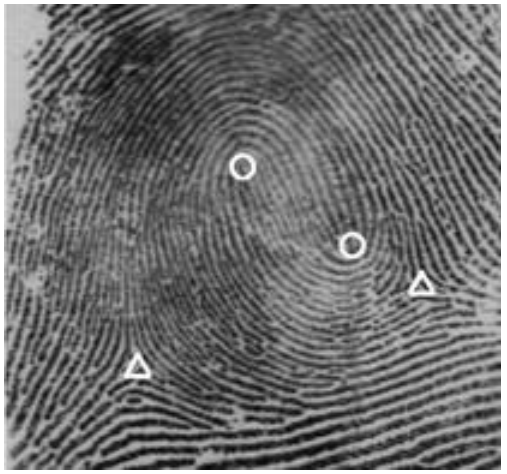


Right Loop

Tented Arch



Whorl

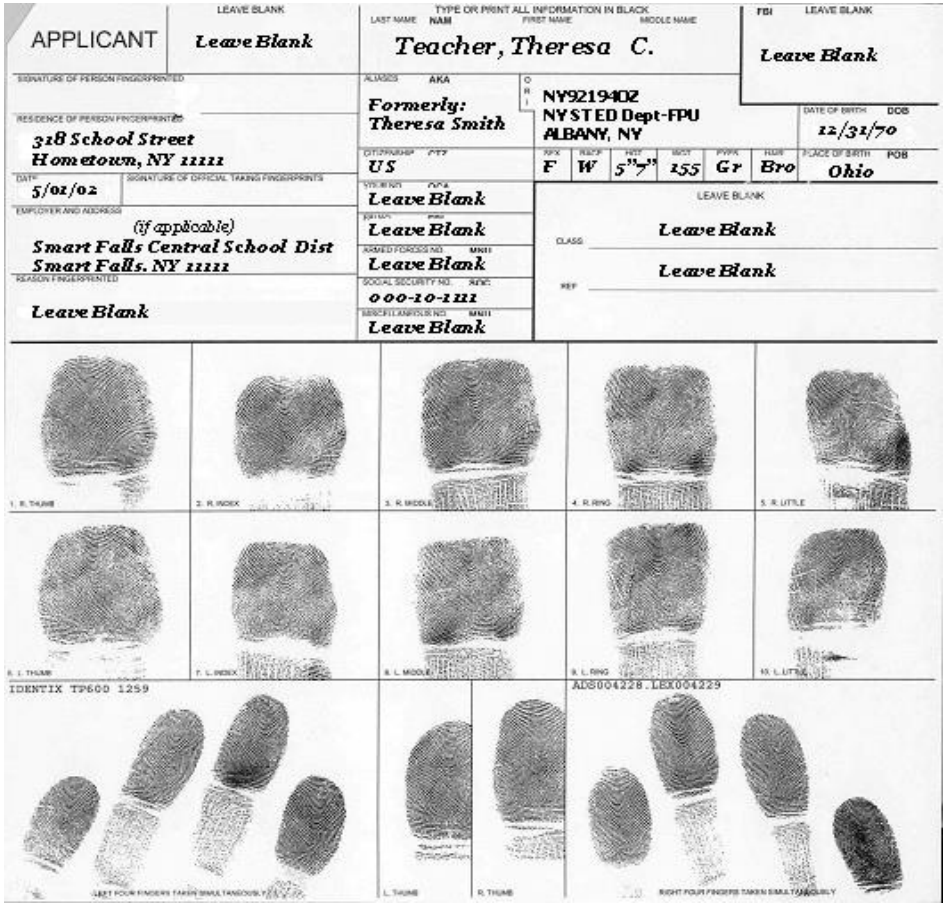


Twin Loop

Scotland Yard (1905)

Pioneers: William Herschel, Henry Faulds, Francis Galton, Juan Vucetich and Edward Henry

FBI (1924)



Tenprint card

Partial fingerprint from a crime scene

- Identify Repeat Offenders (background search): TP to TP comparison
- Crime Scene evidence: Partial to TP comparison

Manual Fingerprint Matching

Michigan State Police Fingerprint Bureau (circa 1960)

Automatic Comparison of Fingerprint Patterns

(Trauring, Nature, 1963)

"It is the purpose of this article to present, together with some evidence of its feasibility, a method by which decentralized automatic identity verification, ***such as might be desired for credit, banking or security purposes****, can be accomplished through automatic comparison of the minutiae in finger-ridge patterns."*

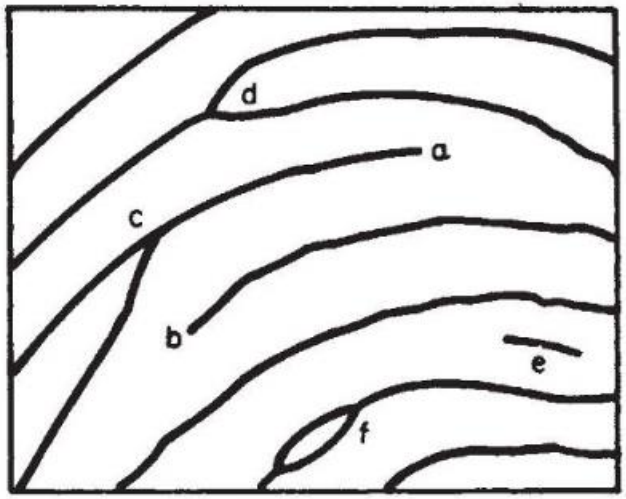


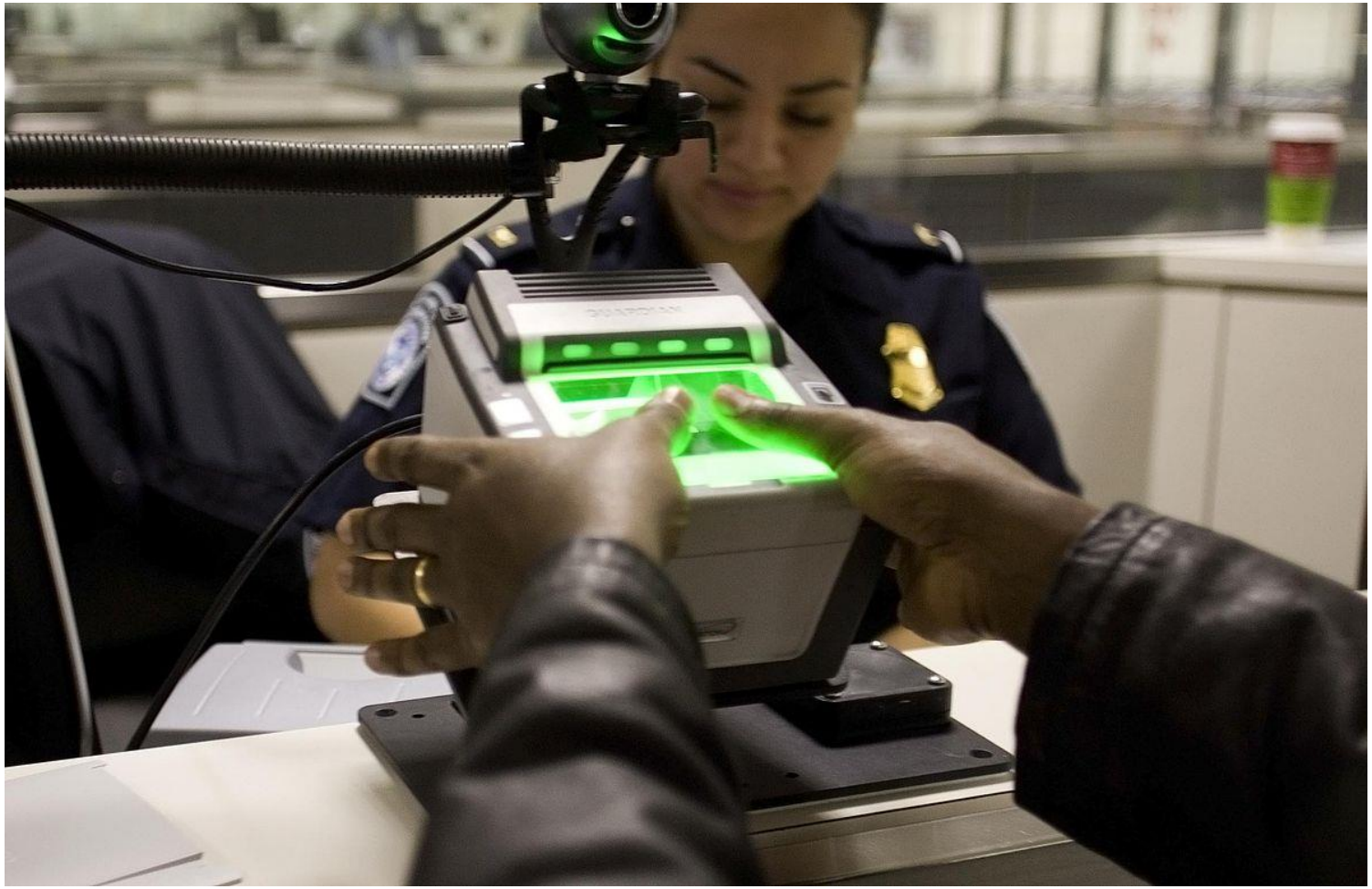
Fig. 1. Portion of fingerprint pattern (diagrammatic, enlarged) after Galton, showing minutiæ. *a* and *b* are ridge ends, *c* and *d* are ridge branchings or valley ends, *e* is an island, and *f* is an enclosure. The ridge end and valley end are the principal minutia types, accounting for almost all minutia occurrences

Automated Fingerprint Identification Systems (AFIS)

Michigan State Police AFIS (1989): 725K TP database; 4.8K TP-to-TP searches; no latent-to-TP search; 15K comparisons/sec.

9/11 Terrorist Attacks (2001)

US-VISIT (2003)



Immigration Check

Incheon airport, Seoul

Mexico immigration

NeoScan 45 fingerprint scanner is used by US ICE to run remote ID checks

Transaction & Access Control

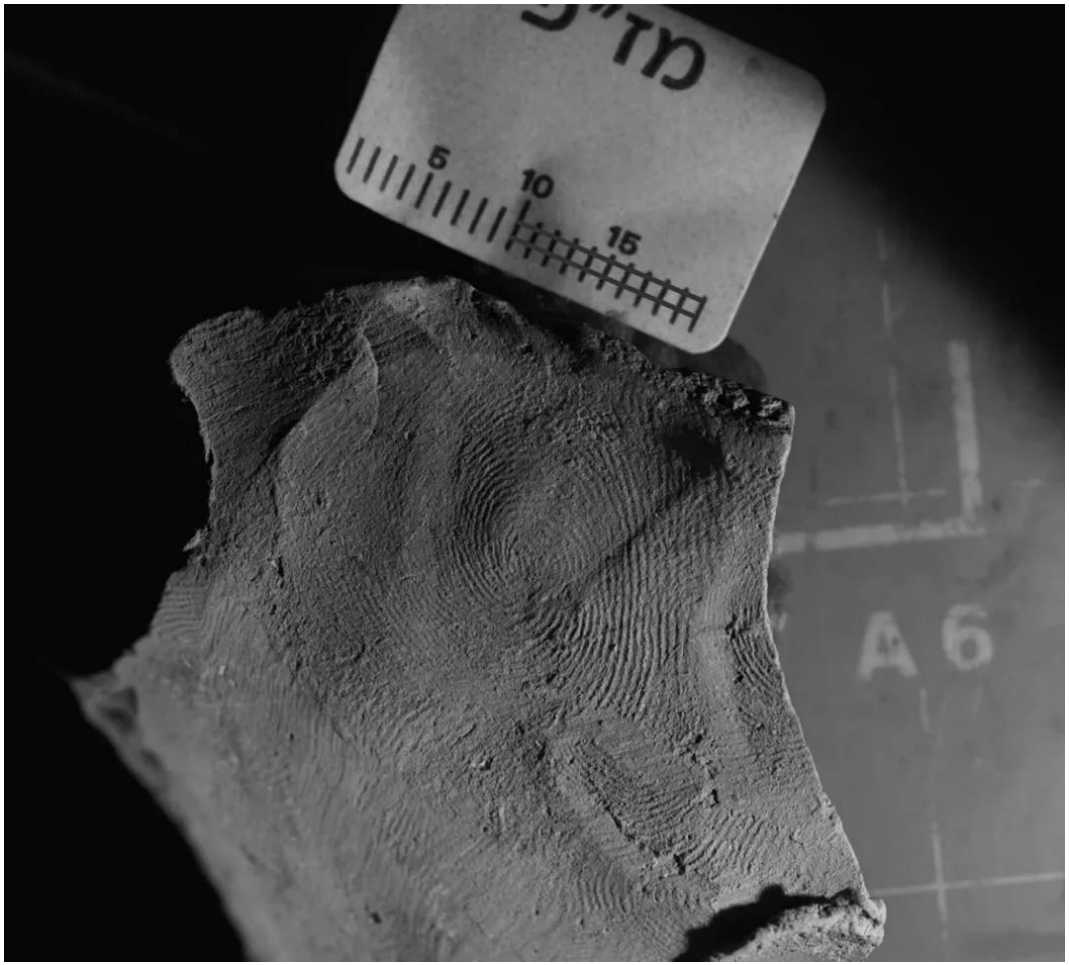
Meijer supermarket, Okemos

Fingerprint time clock

MSU Federal Credit Union

Disney Parks

What Fingerprints Tell Us About Jerusalem's Ancient Artisans



In an unusual collaboration, archaeologists in Israel are working with police to analyze prints left on 5th or 6th-century pottery shards

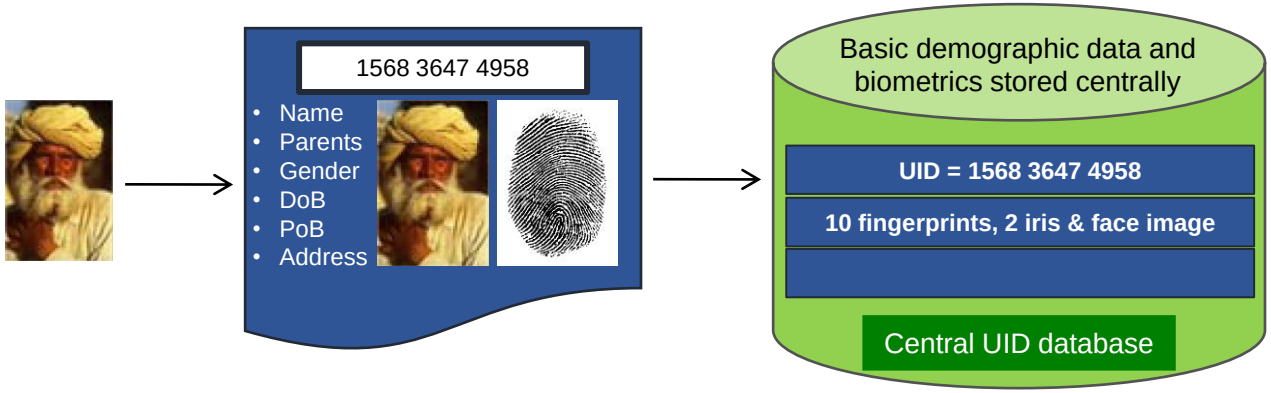
Scores of the fingerprints were identical, leading Hefetz to conclude that one individual was the primary potter. Nora Rajs / Division of Identification and Forensic Science, Israel Police.

https://www.smithsonianmag.com/history/what-fingerprints-tell-us-about-jerusalems-ancient-artisans-180981238/

Aadhaar:

World's Largest Biometrics System (2009)

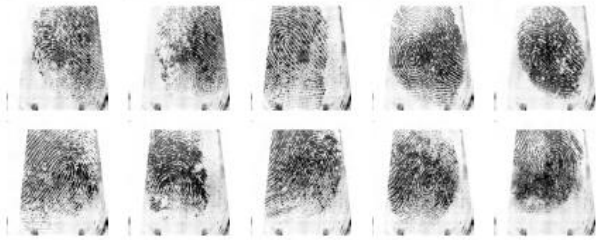
"Issue a 12-digit unique identification number (UID) to Indian residents that can be used to eliminate duplicate and fake identities."



Enrollment (~1.4 billion), de-duplication, authentication (~80 million/day)

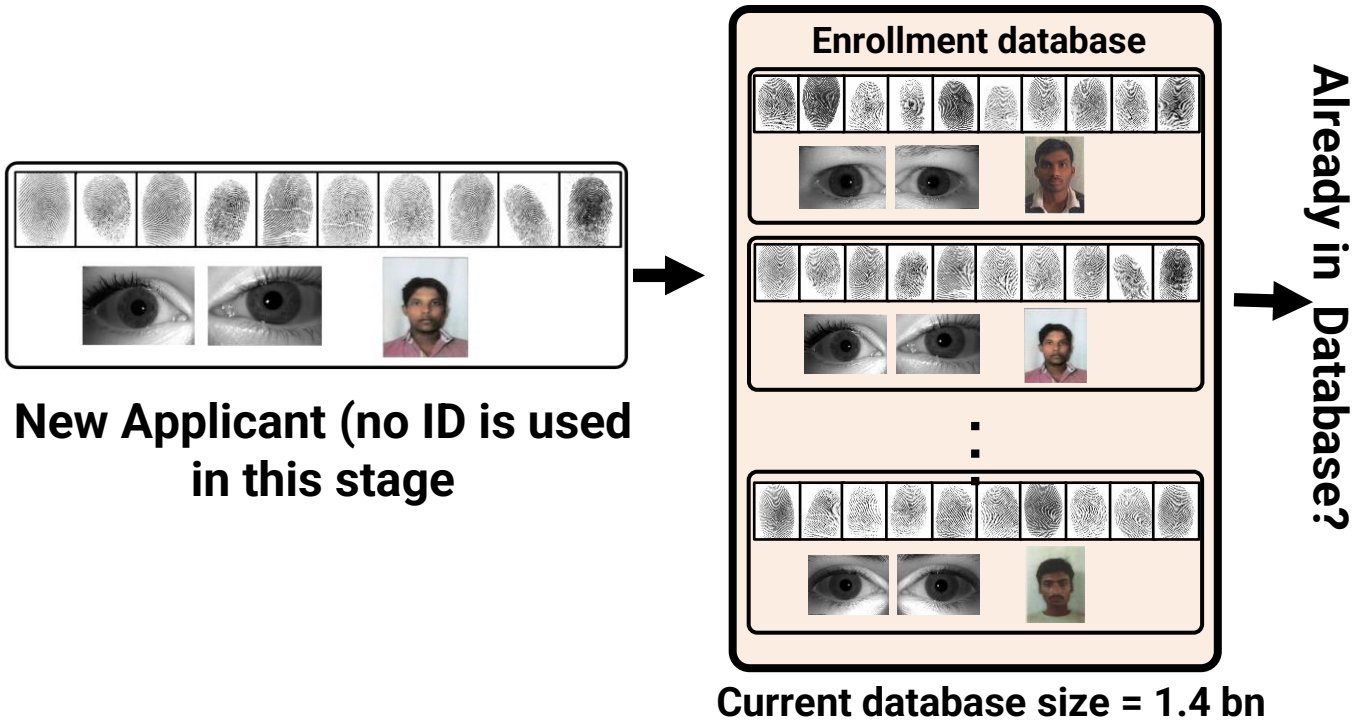
https://uidai.gov.in/

Enrollment



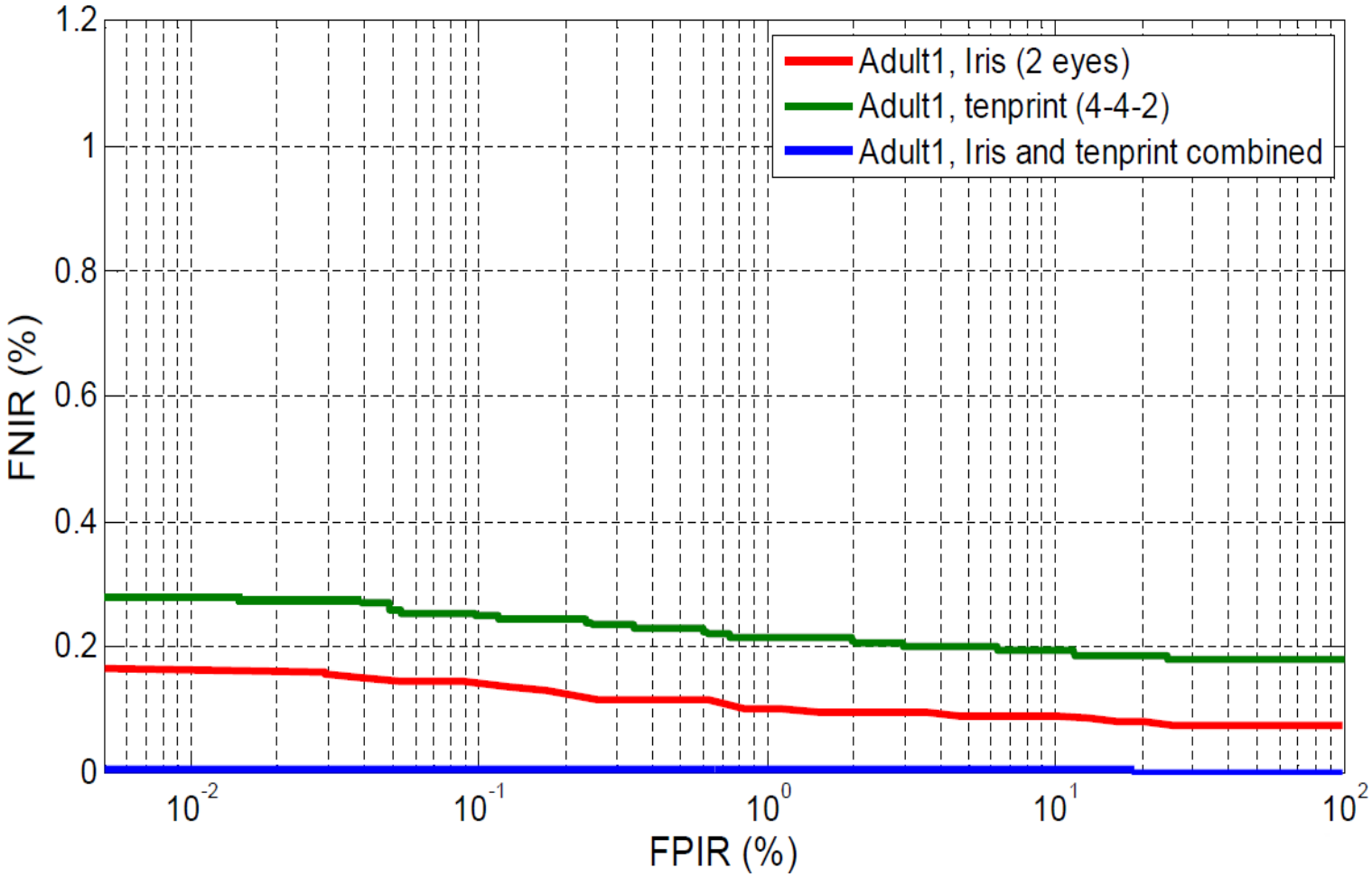
- 10 slap (4-4-2) fingerprints, 2 irises & face image are captured along with minimal demographic information
- Minimum age of enrollment is 5 years; re-enrollment at age 15

De-duplication (1:N Comparison)



- Is the person already enrolled?
- In practice, no single biometric trait is able to distinguish among 1.4 billion individuals

Improved Accuracy of Biometric Fusion



- FPIR: Fraction of non-mated searches where one or more enrolled identities are returned at or above the threshold
- FNIR: Fraction of mated searches where the enrolled mate is outside the top R rank or comparison score is below the threshold

Authentication (1:1 Comparison)

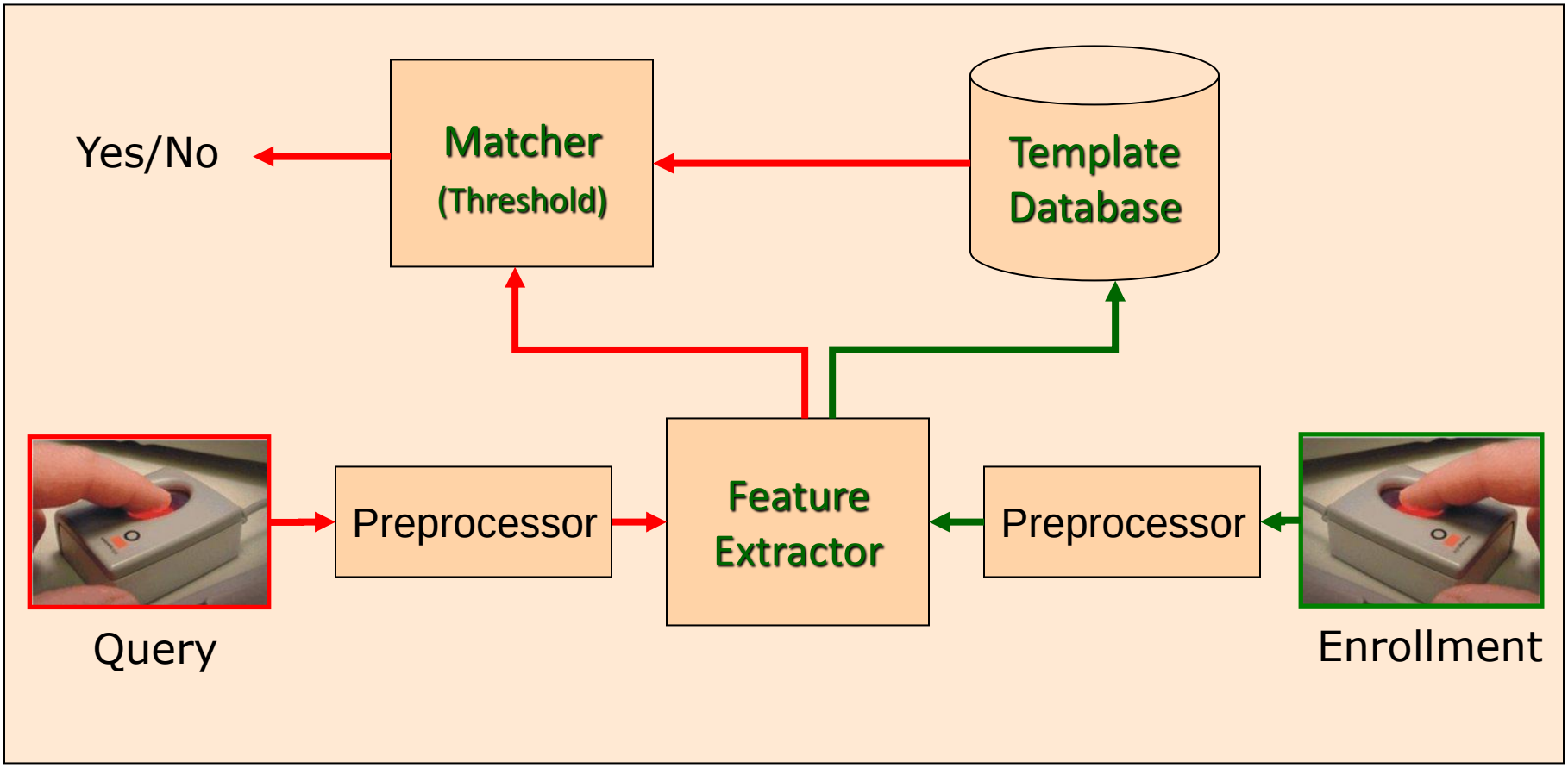
~80 million (2-factor) authentications/day; 12-digit Aadhaar + fingerprint

https://uidai.gov.in/aadhaar_dashboard/auth_trend.php

Social Good vs. Privacy

- "*Aadhaar gives dignity to the marginalized. Dignity to the marginalized outweighs privacy*" - Justice Sikri, Indian Supreme Court (Sept 2018)
- Enrolled biometric data never leaves Aadhaar server and is never shared with any government or non-government entity

Fingerprint Recognition Pipeline

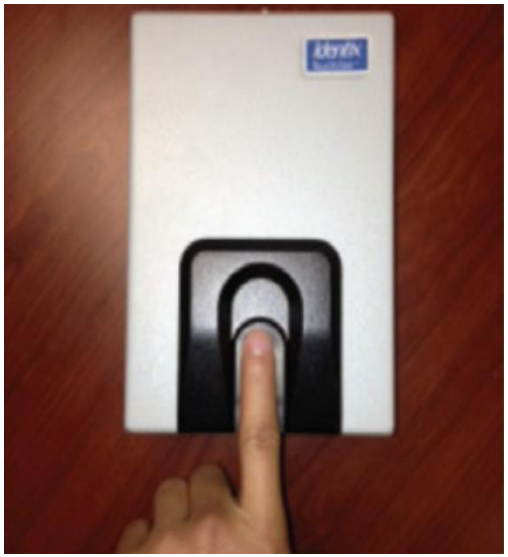


D. Maltoni, D. Maio, A. K. Jain, and J. Feng. Handbook of Fingerprint Recognition, 3rd Edition, Springer, 2022

Working of a Fingerprint System

Sensing

1892
Juan Vucetich
Ink and Paper



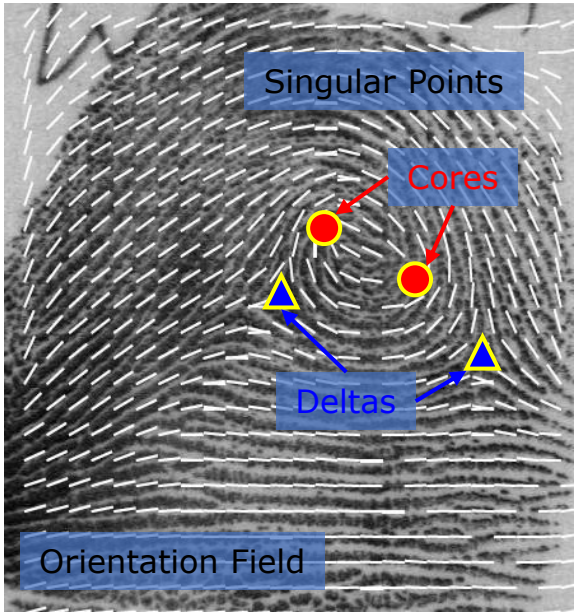
1990
Optical sensor

1990
Capacitive sensor

Fingerprint Representation

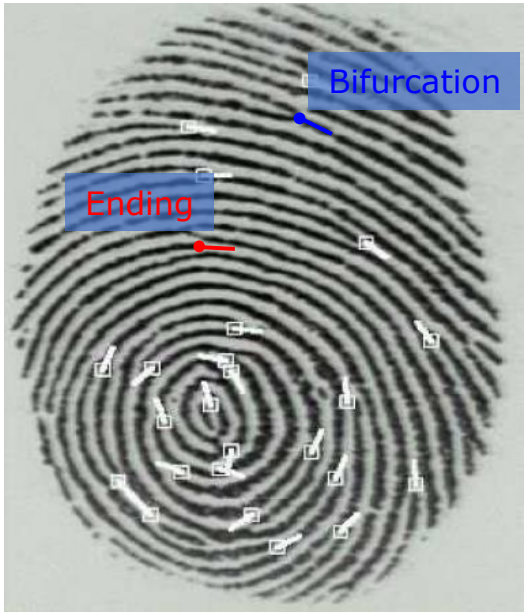
Level-1

Ridge flow and pattern type



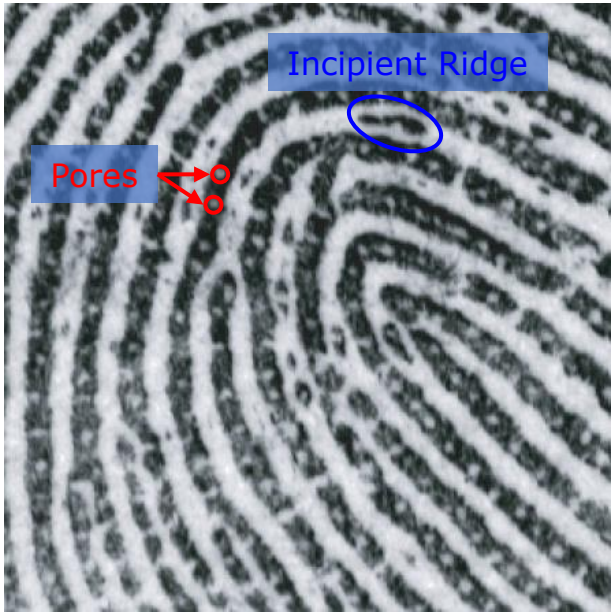
Level-2

Minutiae



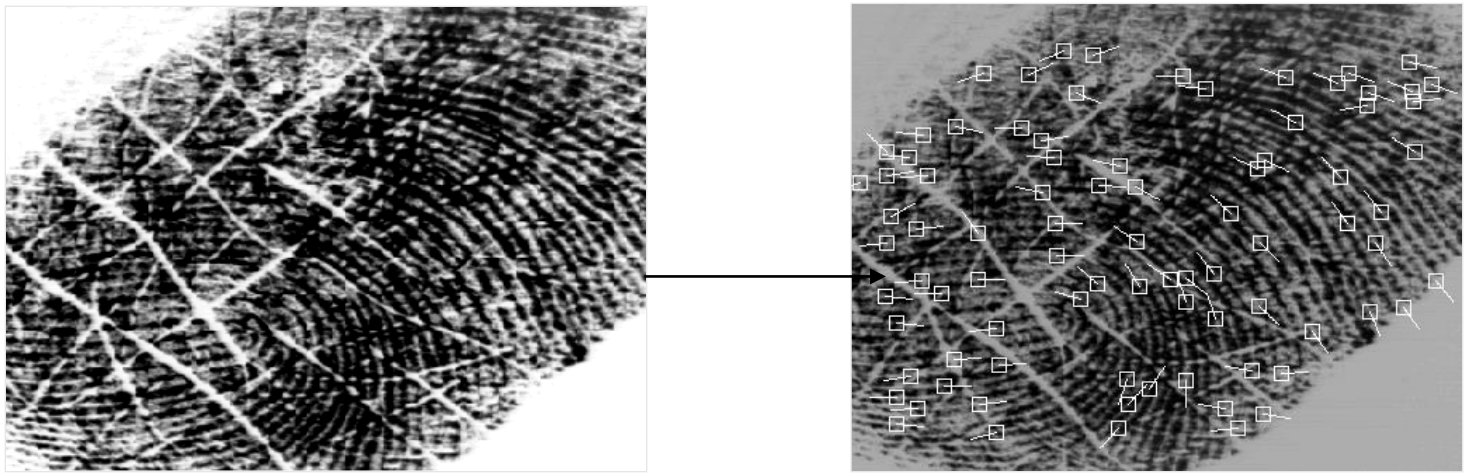
Level-3

Pores and incipient ridges

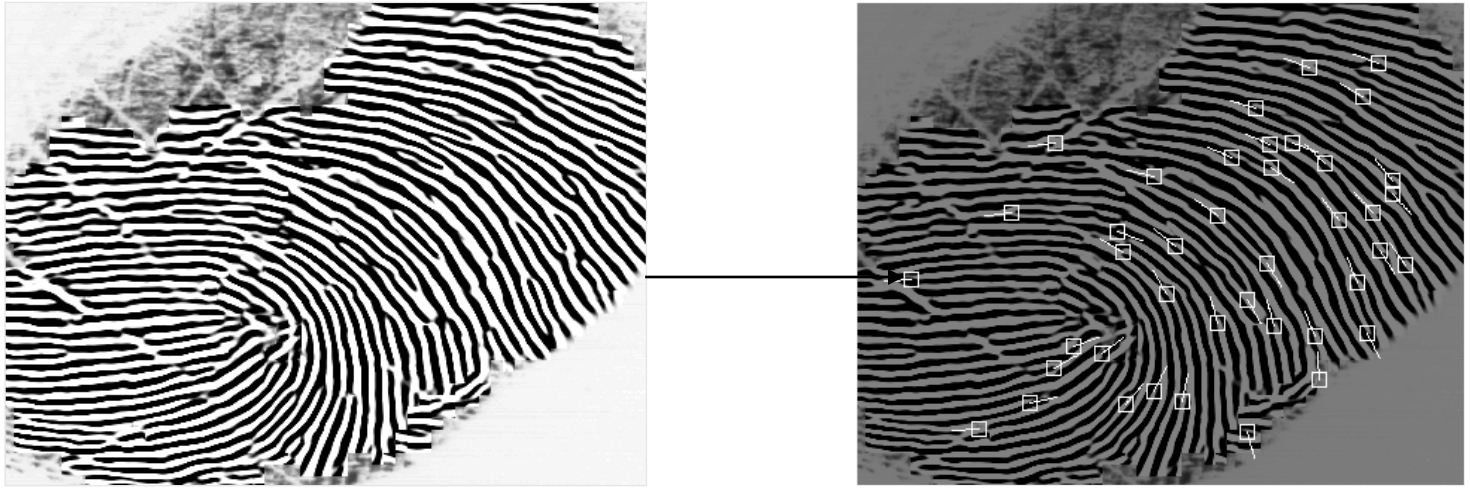


Template: A compact representation of fingerprint features

Fingerprint Enhancement



Minutiae extraction before enhancement

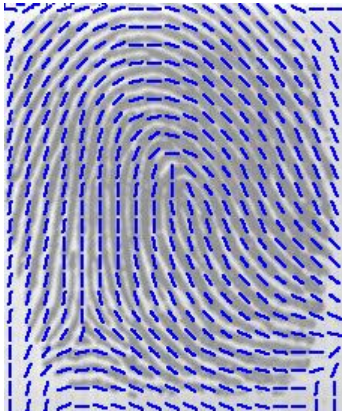


Minutiae extraction after enhancement

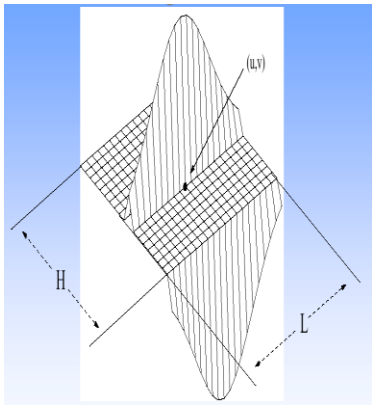
Hong, Wang and Jain, IEEE Trans. PAMI, 1999

Minutiae Extraction

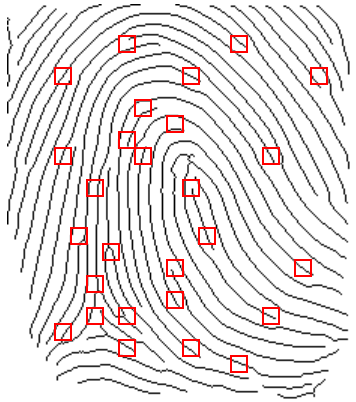
Input Image



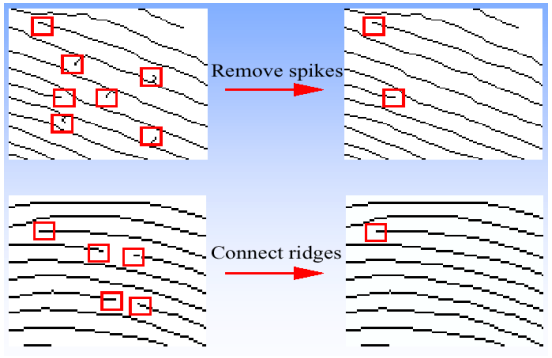
Ridge Flow



Ridge Filter



Ridge Thinning
Minutiae Detection

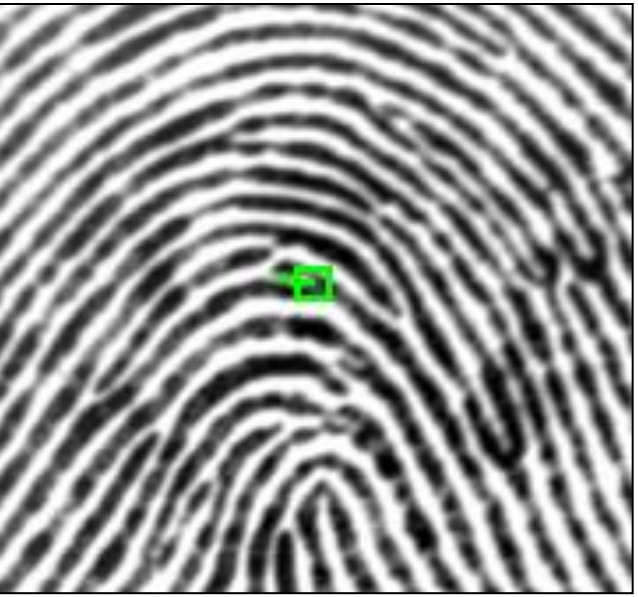


Postprocessing

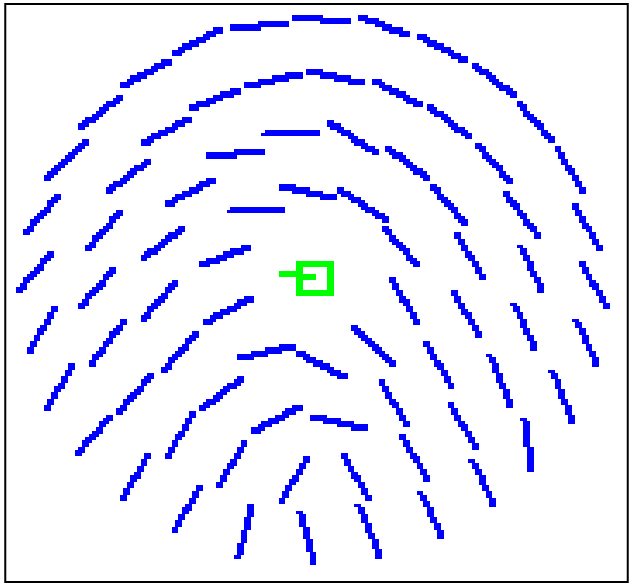
Extracted Minutiae

Minutiae Descriptors

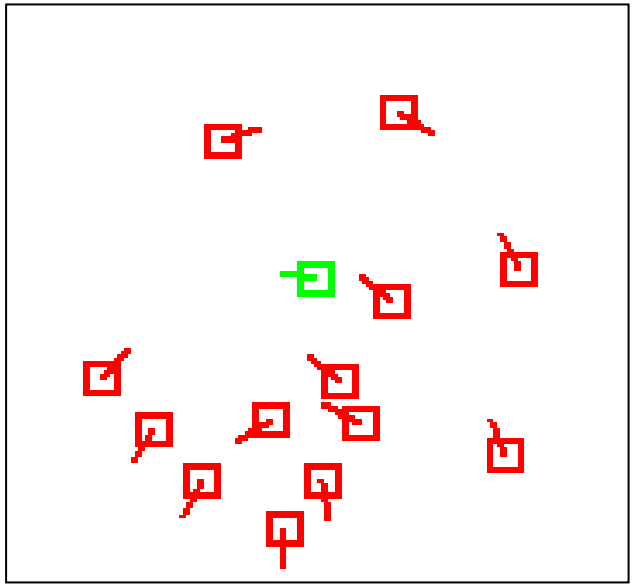
- Ridge Flow-based Descriptor
  - Ridge flow values in the minutiae neighborhood
- Neighboring minutiae-based Descriptor
  - Set of minutiae in a local neighborhood



Minutia Neighborhood

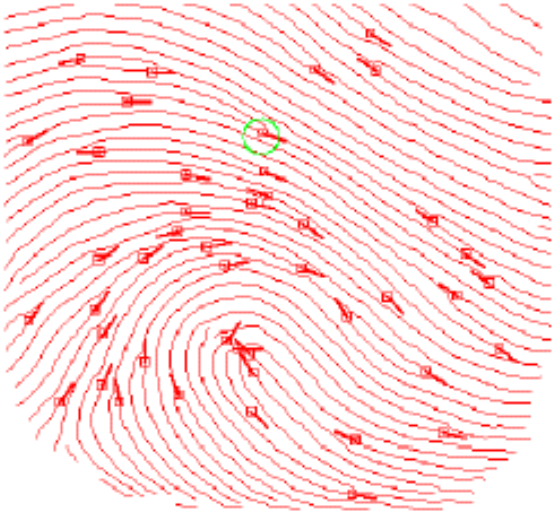


Flow-based Descriptor

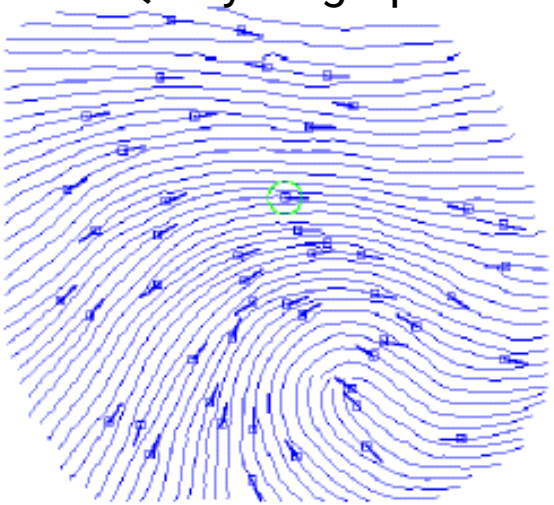


Minutiae-based Descriptor

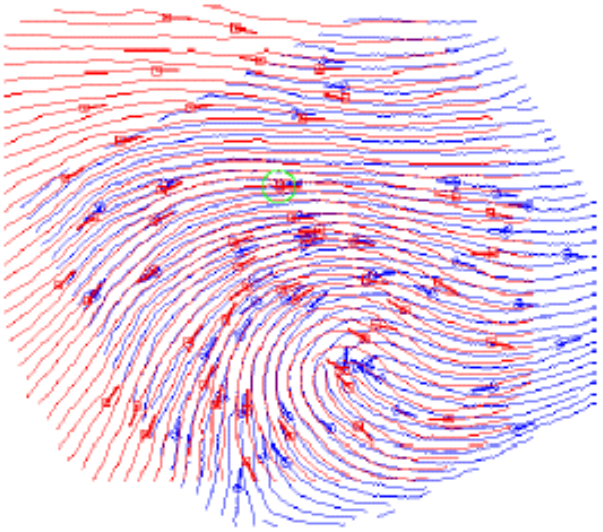
Alignment

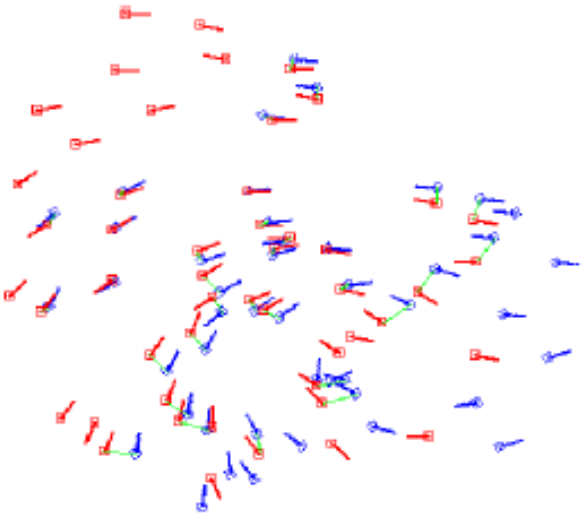


Query Fingerprint



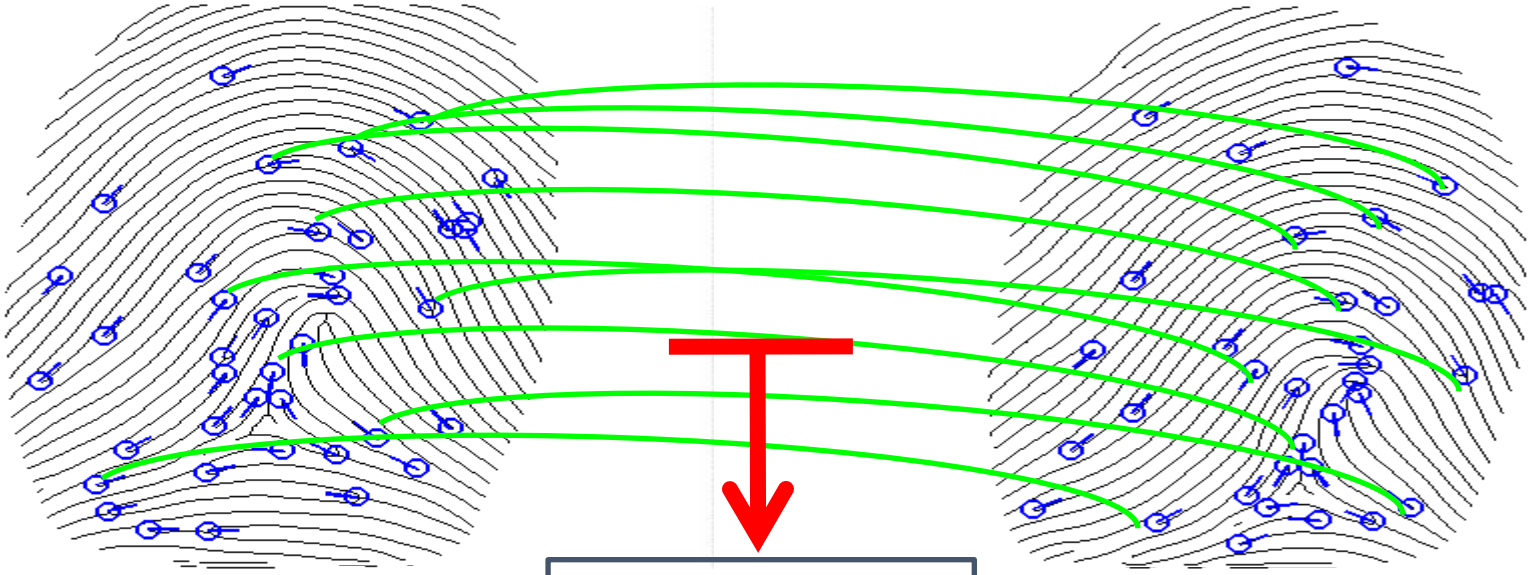
Gallery Fingerprint



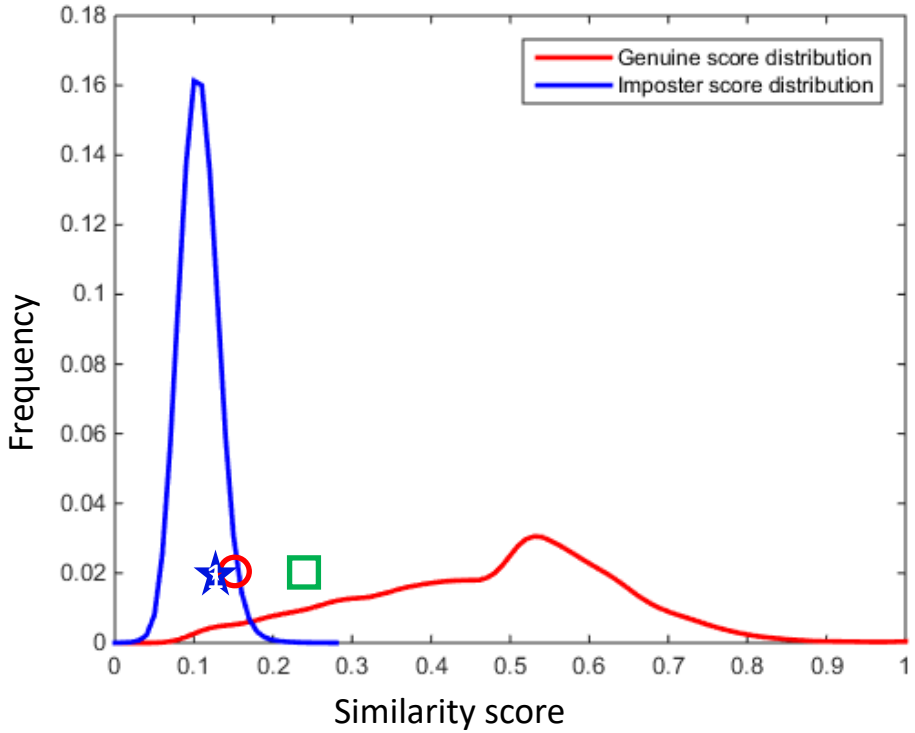


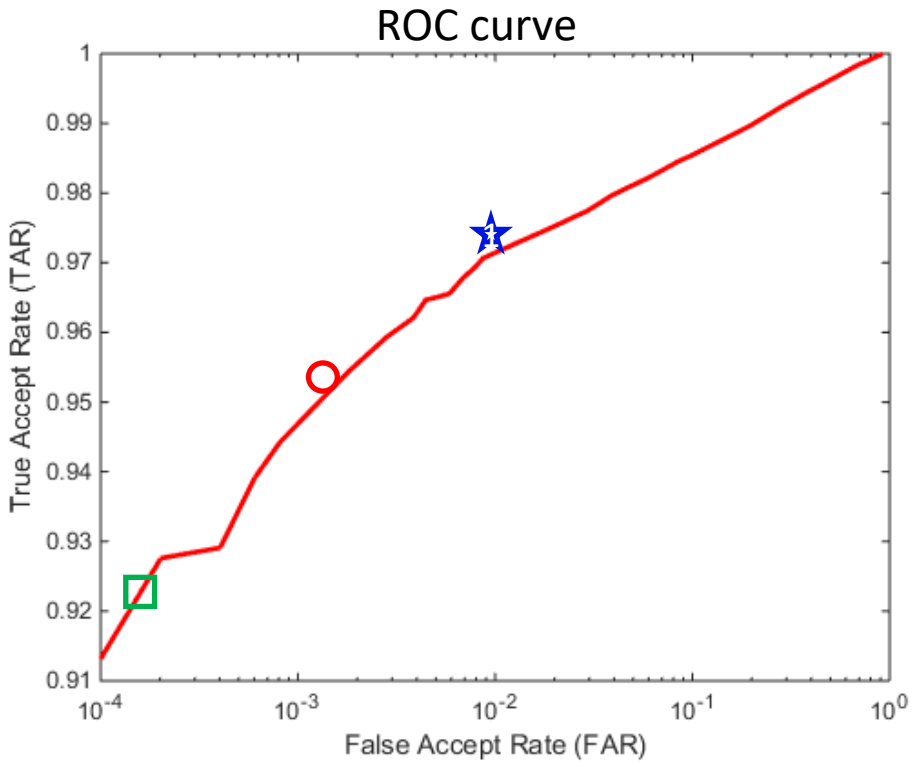
Jain, et al. An Identity Authentication System Using Fingerprints, *Proc. IEEE, 1997*

Fingerprint Comparison



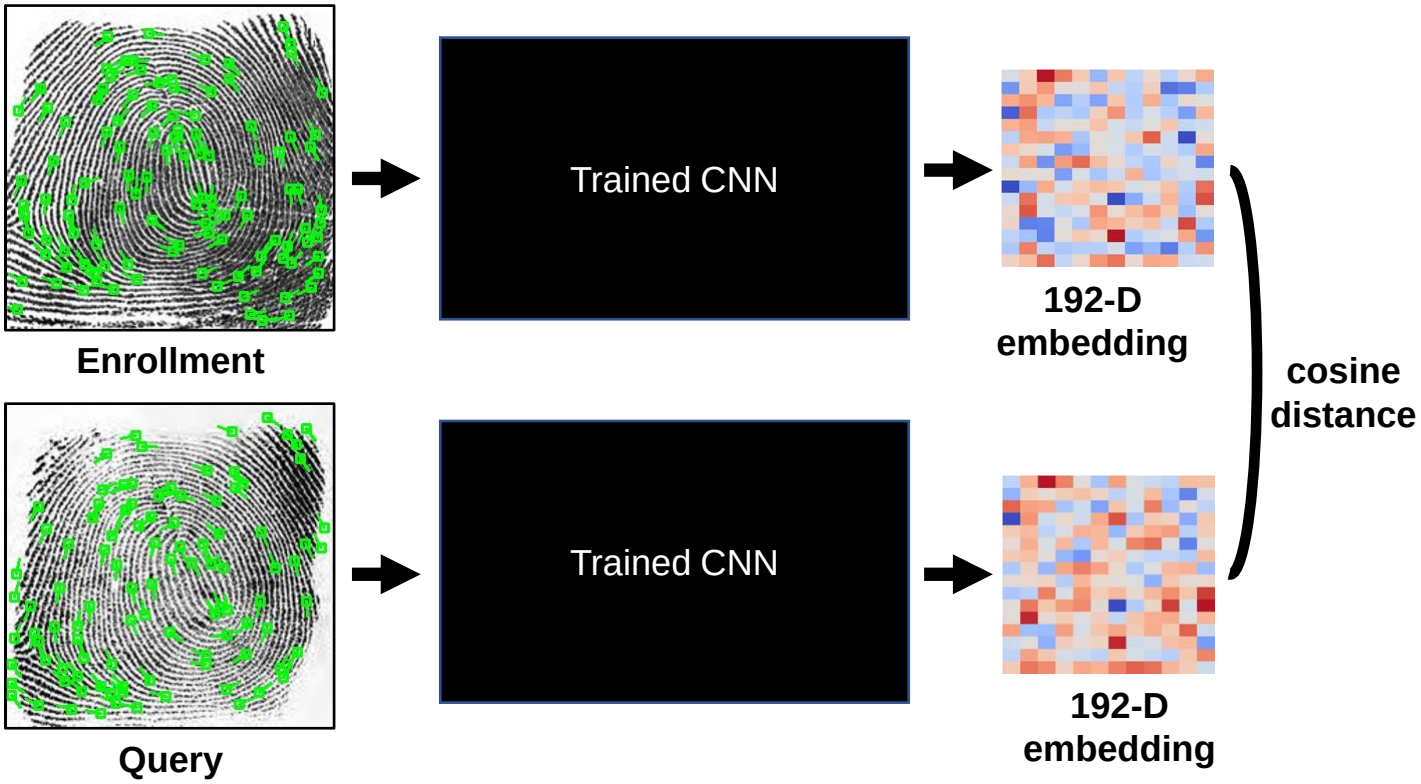
Recognition Performance





Threshold determines tradeoff between FAR & FRR

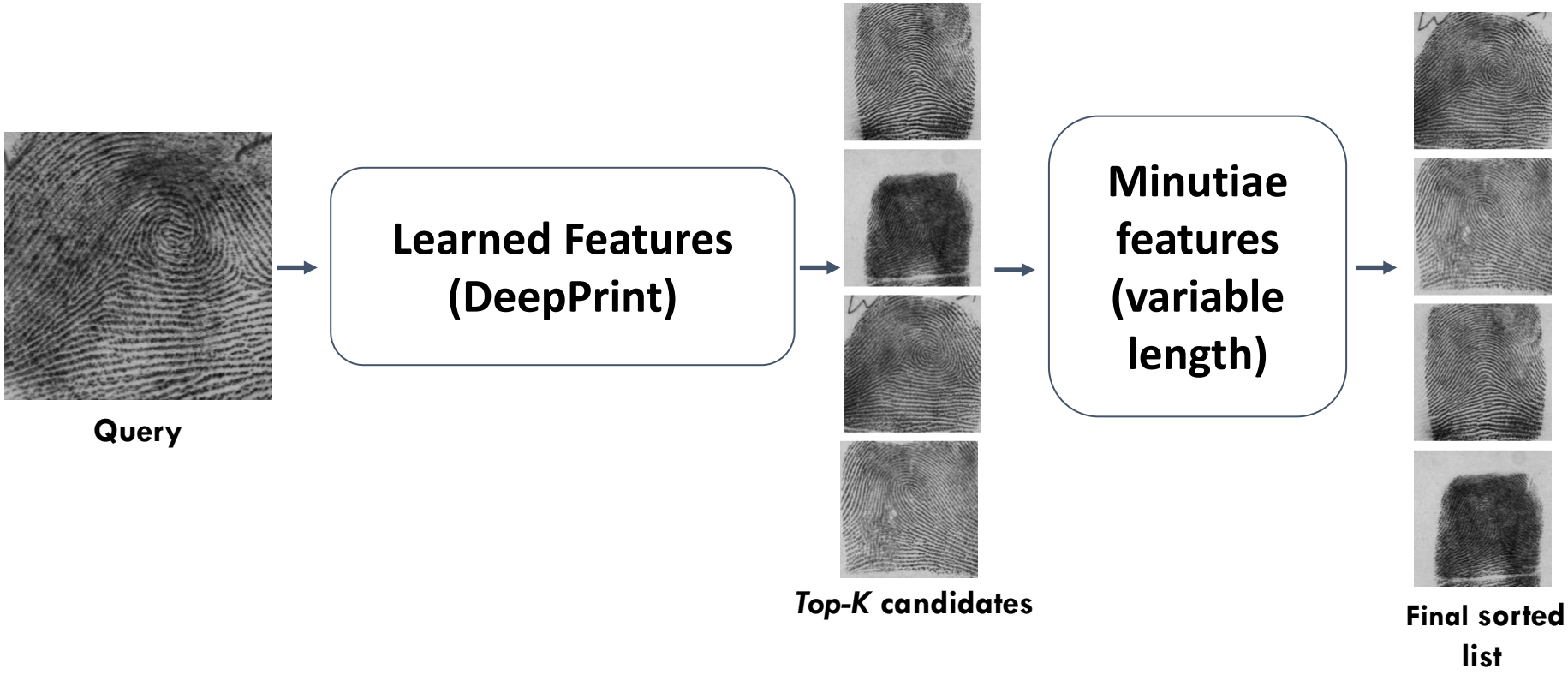
Hand-crafted vs. Learned Features



Learn a **fixed-length feature vector**; computing cosine distance is extremely fast

J. J. Engelsma, K. Cao and A. K. Jain, "Learning a Fixed-Length Fingerprint Representation", in *IEEE Trans. Pattern Analysis and Machine Intelligence*, 2019.

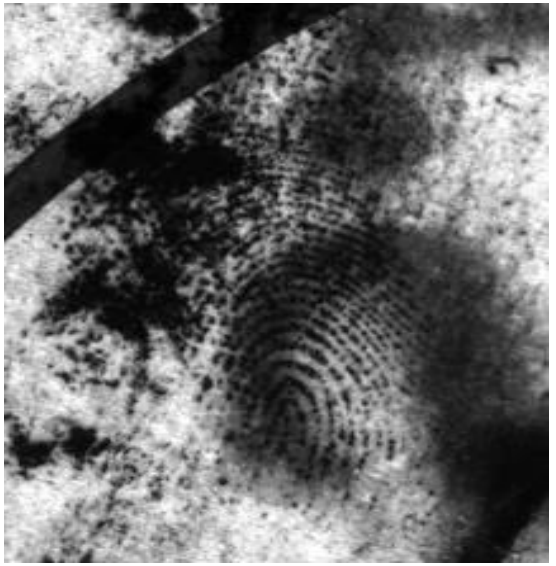
Two-Stage Search



State-of-the-Art Performance

Rolled prints

Plain prints



Latent prints

- Authentication: TAR of 99.9% @FAR = 0.001%
- Retrieval (search)
  - Plain prints: 99.3% (100K background gallery)
  - Latent Prints: FNIR = 0.0795 @ FPIR = 0.01 (516 probes, gallery size= 1.6 million)

Performance depends on quality of images in the evaluation set

https://www.nist.gov/programs-projects/nist-evaluation-latent-fingerprint-technologies-elft

System Requirements: More than Accuracy

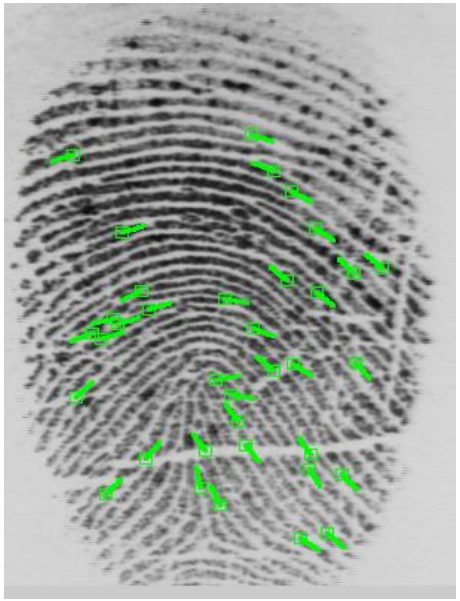
- Usability
- High throughput
- Low error rates
- Day/night operation
- Robust to finger condition: wet, dry,..
- Minimize Failure to enroll
- Return on investment
- Embedded system
- Template security
- Match on device

- 100K visitors/day to Disney Park, Orlando
- Initial deployment 2005

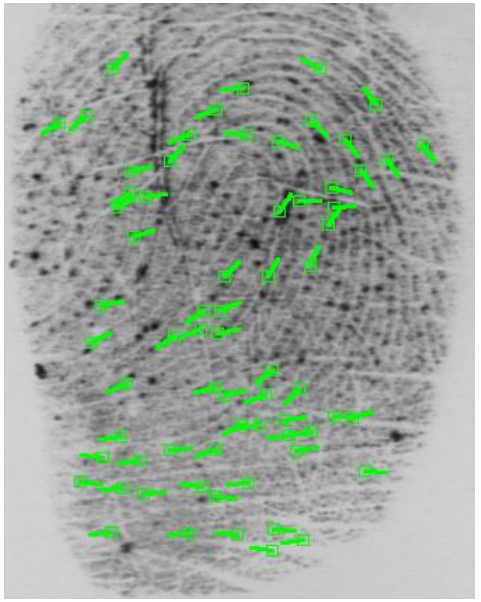
Challenges/Opportunities

Noisy Images

No. of false minutiae = 0



No. of false minutiae = 7



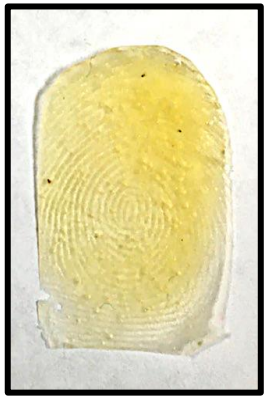
No. of false minutiae = 27

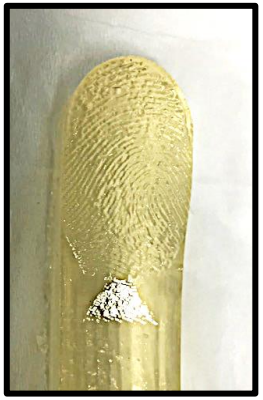
Presentation Attacks


Liquid Latex Body Paint


PlayDoh (Orange)


Monster Liquid Latex


Wood Glue


Gelatin


Crayola Model Magic


Au/Ti Coating


2D Printed on Transparency


2D Printed on Matte Paper


Ecoflex (Silicone)


Nanotips Coating


BarePaint Coating


Silver Colloidal Ink Coating


TangoPlus Ag Coating on VeroBlack

Chugh, Kai and Jain, "Fingerprint Spoof Buster: Use of Minutiae-centered Patches", IEEE TIFS, 2018

Which Images Are Spoof?





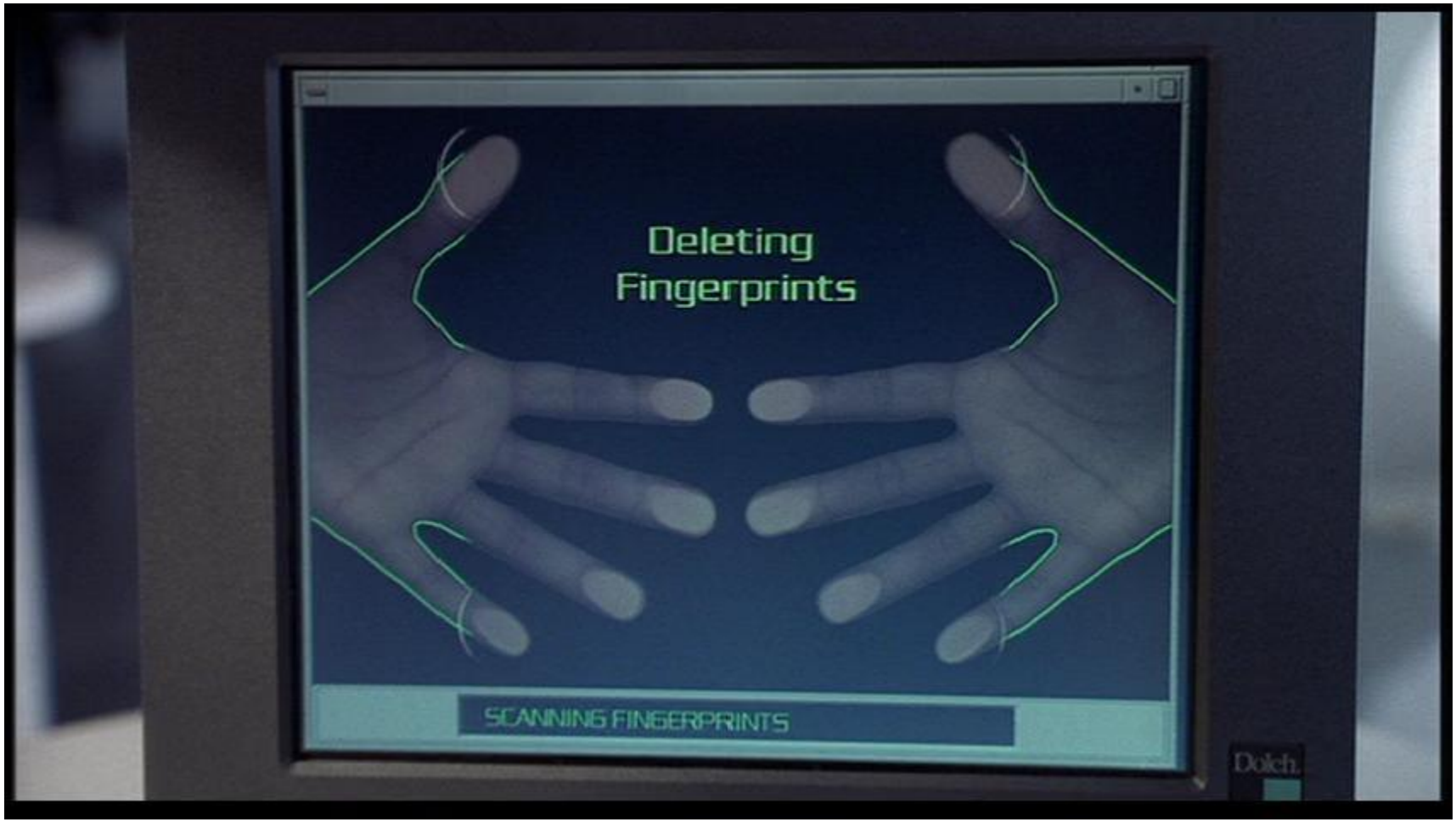
Chugh, Cao, and Jain, "Fingerprint Spoof Buster: Use of Minutiae-centered Patches", IEEE TIFS, 2018

Which Images Are Spoof?





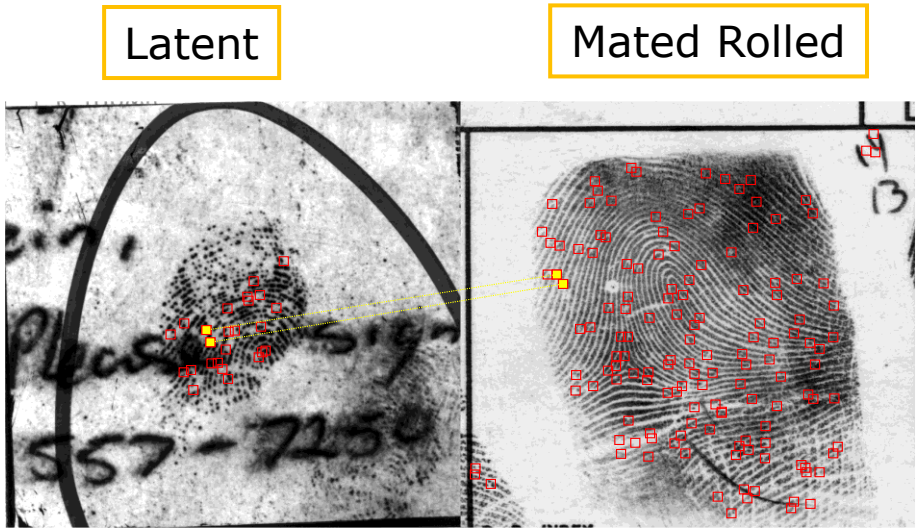
Fingerprint Obfuscation



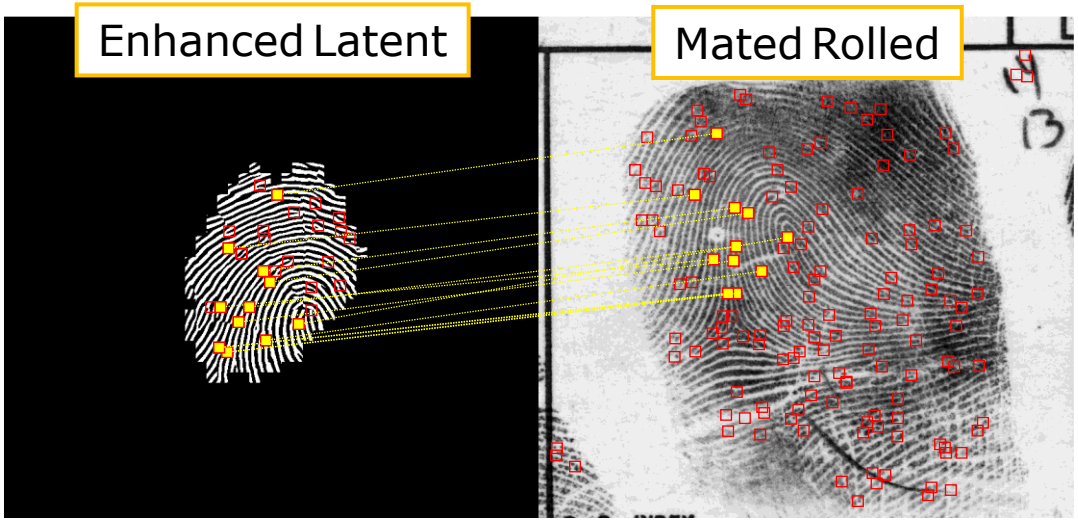
Will Smith in “Men in Black” (1997)

S. Yoon, J. Feng and A. K. Jain, "Altered Fingerprints: Analysis and Detection", *IEEE Trans. Pattern Analysis and Machine Intelligence*, 2012.

Latent Fingerprint Recognition



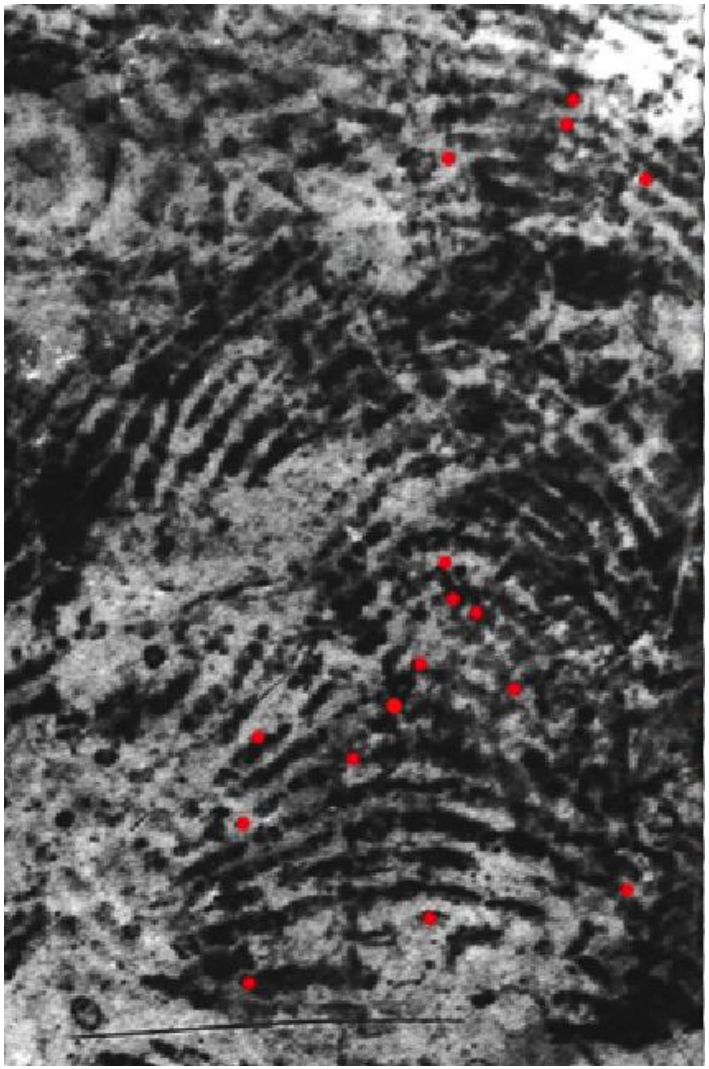
 # Matched minutiae = 2
Similarity score = 3



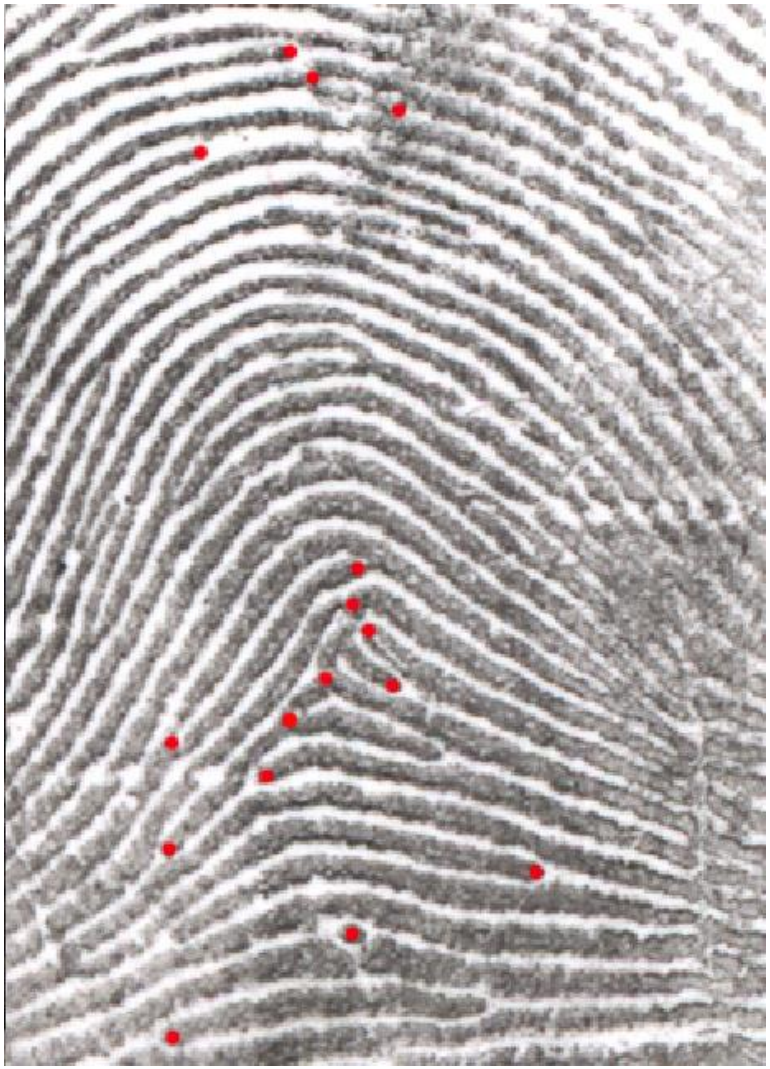
 # Matched minutiae = 13
Similarity score = 38

S. A. Grosz, A. K. Jain, "Latent Fingerprint Recognition: Fusion of Local and Global Embeddings", IEEE Trans. Information Forensics and Security, 2023.

Wrongful Conviction: Madrid Bombing (2004)



Partial print on a duffel bag



Brandon Mayfield's prints in file

Fingerprint Image Generator

- Largest public-domain fingerprint dataset: NIST SD302 with 2K unique fingers and 25K images
- Synthesize multiple impressions/finger for new identities

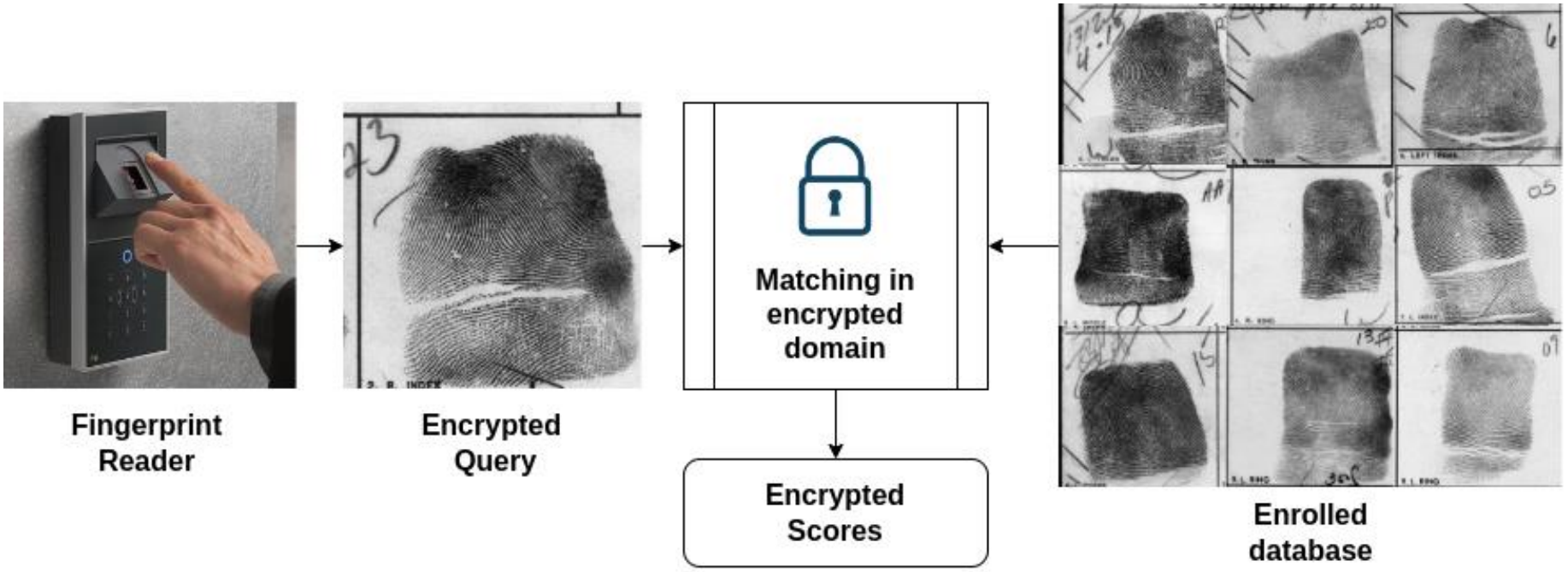
- Data augmentation with synthetic images improves recognition model performance

- *Engelsma, Grosz and Jain, "PrintsGAN: Synthetic Fingerprint Generator", IEEE TPAMI, 2022*
- S. A. Grosz, and A. K. Jain "Universal Fingerprint Generation: Controllable Diffusion Model with Multimodal Conditions", arXiv preprint arXiv:2404.13791, Mar 2024.

Real or Synthetic?

Real or Synthetic?

Privacy Preserving Authentication



Engelsma, Jain and Boddeti, "HERS: Homomorphically Encrypted Representation Search", IEEE T-BIOM, 2021.

Summary

- Fingerprint recognition has been in use for over 100 years
- Fingerprint evidence is accepted in courts for conviction
- Hundreds of millions worldwide willingly use it everyday for mobile unlock & payment, social benefits, ……
- Need to understand application requirements
- Challenges & opportunities: need to continually improve accuracy and throughput, template security and PAD, contactless fingerprints