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A Forward-Looking Multi-Factor Authentication (MFA) Model for Cultural Heritage Art Objects That Can be Trained to Look Backwards

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Abstract

Authentication of cultural heritage objects can be understood as a statistical decision problem in which the objective is to minimize the probability of false identification. Traditional approaches rely on provenance records and expert judgment, while scientific analyses are typically applied as independent examinations without formal integration into a unified decision framework.

This paper proposes a multi-factor authentication (MFA) model in which intrinsic physical characteristics, the object's inherent reality, are treated as object-intrinsic signals that can be combined into evidence channels, termed authentication factors. When such factors are statistically independent, the probability of false identification decreases multiplicatively[6,7,8], providing a formal mechanism for achieving high-confidence authentication.

We introduce the concept of invariant physical factors, stable, measurable properties arising from an object's material composition, structure, and fabrication history. These factors can serve as independent evidence channels that become inputs to an MFA framework. The factors are assembled into identity vectors that enable statistical comparison between objects.

A key implication of this model is that authentication measurements accumulate over time, forming a structured dataset that supports both forward authentication decisions and backward-looking analysis across collections.

1. ***Motivation:*** Cultural heritage authentication is increasingly challenged by expanding markets and the growing sophistication of modern forgery techniques. Traditional approaches rely heavily on provenance documentation and expert connoisseurship, both of which are subject to uncertainty and dispute.

   Scientific methods, including spectral analysis[3,4], chemical characterization, and high-resolution imaging, provide valuable insight but are typically applied independently. The lack of a unifying statistical framework limits their collective effectiveness, producing valuable but fragmented evidence.

   In contrast, other domains such as information security have adopted multi-factor authentication (MFA) frameworks where independent evidence channels are combined to reduce the probability of false identification. Extending this concept to physical cultural heritage objects motivates a reexamination of how scientific measurements can be defined, combined and interpreted statistically to create a physically grounded authentication protocol for objects such as paintings.

2. ***Problem:*** Recent work has suggested that MFA principles can be applied to physical objects by combining multiple independent measurements into a unified authentication decision. However, unlike digital systems, physical objects do not inherently provide discrete authentication tokens. The central challenge is identifying and extracting measurable, stable, and independent intrinsic physical features that exhibit measurement invariance under observation conditions and can be fashioned into authentication factors.

   Such features must:
   - Be invariant over time under normal conservation conditions
   - Be difficult to replicate through forgery
   - Be statistically independent or exhibit low inter-factor correlation[6,7]
   - be quantifiable within a reproducible measurement framework

   Without such factors, MFA cannot be realized in a physical domain.

3. ***Approach:*** We consider classes of invariant physical factors derived from measurable properties of an object's material composition, structure, and fabrication history. These factors form orthogonal and independent evidence channels suitable for MFA.

   Representative factor classes include:
   - spectral reflectance behavior[1,2,9]
   - micro-topographic surface structure
   - chemical composition signatures
   - refractive index transitions
   - fabrication-derived microstructure and stochastic patterns

   Each invariant measurement channel produces an independent identity factor that can be combined with other factors into an authentication vector. These are combined as:

   $$F = (F_1, F_2, \ldots, F_n)$$

   This representation enables statistical comparison between objects in a high-dimensional feature space.

4: ***Results:*** The statistical basis for MFA holds that when invariant factors are independent, false identification probability decreases multiplicatively:

$$P(false) = \prod_{i=1}^{n} FAR_i$$

where FAR$_i$[6,7,8] is the false-accept rate of the i-th factor. This relationship provides the formal statistical basis for applying MFA to physical objects.

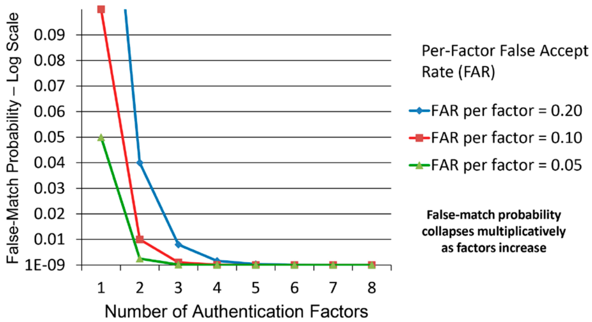

Figure 1 – Multiplicative Suppression of False-Match Probability in MFA

The identity vector**:**

$$F = (F_1, F_2, \ldots, F_n)$$

then defines a position in high-dimensional space describing the object's physical state. Authentication becomes a statistical comparison between identity vectors derived from different measurements or objects. The aggregation of independent factors increases discriminatory power and reduces ambiguity arising from any single measurement channel. This results in a resolution of measurement ambiguity.

Traditional colorimetric and imaging methods can exhibit measurement degeneracy (e.g., metamerism)[1,2], where distinct physical states produce indistinguishable measurements under limited observation conditions. By incorporating higher-dimensional invariant factors such as full spectral traces, structural features and material signatures, the MFA framework resolves such degeneracies as distinct objects occupying different coordinates in the identity space.

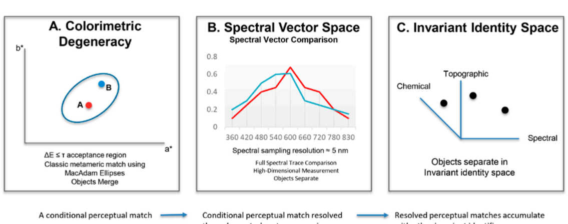

Figure 2 – Measurement Dimensionality and Resolution of Metamerism
(for Illustrative Purposes Only)

Accumulation and retrospective analysis are distinguishing features of this framework where each authentication event generates a calibrated measurement set describing the object. As measurements accumulate across many objects, they form a structured dataset in feature space[6]. Statistical analysis of this dataset can reveal patterns associated with:

- artists and workshops
- material usage
- fabrication techniques
- historical practices

Thus, the system provides both:

- a prospective authentication mechanism and
- a retrospective analytical framework

capable of supporting broader cultural heritage research. Analysis of this space reveals patterns associated with materials, fabrication methods, and artistic practices.

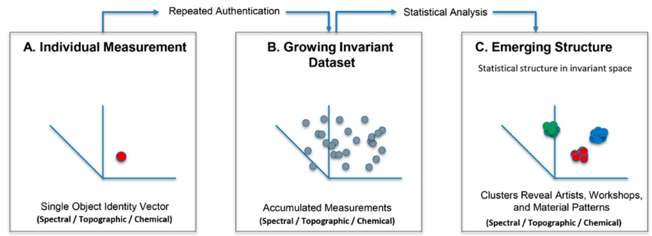

Figure 3 – Authentication Measurements Accumulate Into an invariant knowledge space
(For Illustrative Purposes Only)

5: ***Conclusions****:* This paper establishes a statistical framework for applying MFA to cultural heritage objects using independent, invariant physical factors.

By treating measurable object-intrinsic features as authentication factors and combining them within an MFA model, the probability of false identification can be reduced in a principled and quantifiable manner.

Beyond authentication, the accumulation of invariant measurements enables the construction of a structured knowledge base describing cultural heritage objects. This dual capability, authentication and knowledge generation, represents a fundamental shift from isolated analytical techniques toward an integrated, data-driven paradigm.

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Author Biography

The author, CEO of Spectral Masters Digital Imaging, Inc. develops imaging systems for graphical, medical and military applications, and has been granted multiple hyperspectral imaging patents. Based upon insights gained analyzing CIE protocols and synthetic aperture computational imaging systems, the concept of a unique Multi-Factor Authentication method using only invariant characteristics of an art object was created.