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**Blood Stain Pattern Analysis: A Comprehensive Review of Methods, Reliability of Computerized Analysis, and Future Advancements**

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Abstract

Bloodstain Pattern Analysis (BPA) stands as a precious tool in the crime scene investigation and reconstruction, providing invaluable insights into the circumstances surrounding bloodshed. This comprehensive review delves into the profound significance of BPA, charting its evolution over time while spotlighting recent breakthroughs and identifying potential areas for further research and development, especially within the domain of digital technology.

The fundamental essence of BPA lies in meticulously analyzing the form and dispersion patterns of bloodstains found at crime scenes., which aids investigators in comprehending the deposition of blood on evidence and shedding light on the movements and positions of the individuals and objects involved during the incident. Notably, BPA facilitates differentiating between accidents, homicides, and suicides, as well as identifying bloodstains left by criminals, thus playing a crucial role in ascertaining the circumstances surrounding an incident. Elements like blood velocity and the nature of the impacted surface significantly influence the size and shape of bloodstains, imparting crucial clues for an accurate crime scene reconstruction.A noteworthy application of BPA is in impact spatter analysis on hands, which holds importance for forensic ballistic examiner to recognize the firearm. Studies are discussed, related to sophisticated image processing and computerized techniques for BPA to scrutinize their reliability and accuracy. Cutting-edge advances have been witnessed in the field, including the application of Raman spectroscopy, automated methodologies, and the utilization of software programs like the FARO Scene program. These advancements have substantially elevated the efficacy and capabilities of BPA, empowering forensic investigators with enhanced analytical tools. Despite the remarkable strides made in blood spatter pattern analysis, the review underscores the abundant potential for continued research and development. In particular, refinements in methods for dating dried blood pattern and the evolution of automated techniques for crime scene reconstruction are prime avenues worthy of exploration.

**Keywords:** *Blood, Spatter Pattern, Blood Spatter Pattern Analysis (BPA), Computerized examination, Automated analysis, Impact pattern, Recent Advancements*

1.1 Introduction:

Bloodstain pattern analysis (BPA), is a technique used to reconstruct the events that led to bleeding. By understanding how blood ended up on a wall or other surface, it is feasible to ascertain whether a crime has occurred and if the blood present can serve as evidence of that crime. Bloodstains are classified into different types, each providing a clue to the crime scene. Three primary categories of bloodstains include passive, transfer, and impact stains (1,2)

BPA offers investigators valuable insights in various aspects. Bloodstain pattern analysis is instrumental in identifying the points of convergence and origin of bloodstains, discerning the direction and type of impact responsible for the bloodstain or spatter, and understanding the mechanisms that generated patterns. Additionally, this analysis aids in comprehending the deposition of bloodstains on evidence, as well as potentially revealing the positions of the victim, assailant, or objects at the scene and their potential movement after the bloodshed occurred. By examining spatter patterns, transfers, and other indicators, analysts can classify seemingly haphazardly distributed bloodstains at a crime scene, and reconstructing the sequence of events that transpired after the bloodshed occurred. Moreover, bloodstain pattern analysis can corroborate or challenge statements provided by the accused, offer supplementary factors for estimating the postmortem interval, and correlate with other pertinent laboratory and pathology findings (3).

The form of a bloodstain pattern is significantly impacted by the force applied to propel the blood and the characteristics of the surface upon which it lands. In criminal investigation, the primary responsibility of a bloodstain pattern analyst is to aid in reconstructing events of a reported incident that might have resulted in the presence of stain patterns at a crime scene, including those on clothing items discovered at the location. When blood evidence is collected and stored correctly, it can establish a compelling link between an individual and a criminal act. This particular form of physical evidence demands that the analyst possesses the capacity to identify and comprehend patterns to ascertain how they came into existence. Utilizing the size, shape, distribution, and placement of bloodstains, analysts formulate conclusions regarding the precise sequence of events, as well as potential occurrences, during the incident (1) Suppose the cause of death is established as blunt force trauma to the victim's head. In that case, the blood spatter's pattern and volume should align with the notion of a blunt instrument striking the individual's head once or multiple times. When the spatter is blood that has been expelled from the body, the analyst will review pathologist reports to identify any injuries that might result in blood being present in the victim's nose or respiratory system. If the analyst does not find any blood in these areas, it may allow them to eliminate expiration as a potential cause (2).

**Types of Tests for Detection of Bloodstain**

Before blood can be classified and analysed, it must first be discovered and verified. The reason analysts often rely on the ABC Approach (Appearance, Behaviour, and Context) to bloodstain verification is due to the impracticality of analysing the entire scene for the presence of blood. In cases where chemical tests are required, their application depends on whether the suspected blood is visible or not. Detecting blood can be challenging, particularly when offenders attempt to conceal it by employing cleaning solutions (4)

To further examine blood stain first we have to identify if it is blood or not. There are various methods for detection of blood. The Kastle-Meyer test is a presumptive test that employs the chemical indicator phenolphthalein to potentially detect the presence of haemoglobin (4,5). Although the Kastle-Meyer test is quick, it cannot be directly applied to a bloodstain as it can potentially destroy DNA evidence. As a result, it is most effective to utilize the Kastle-Meyer test when there is an ample amount of blood evidence available(4). Hydrogen peroxide can be employed independently as a valuable method for detecting blood. When hydrogen peroxide comes into contact with blood, the catalase enzyme present in blood facilitates the production of oxygen bubbles. This reaction is classified as an oxidation process, resulting in the formation of visible white foam, making it a discernible indication of presence of blood. Despite its limited sensitivity, hydrogen peroxide remains beneficial due to its cost-effectiveness and its non-interference with DNA, even after being exposed for up to one month (4–6)**.**

Hydrogen peroxide is used to treat both visible and difficult-to-detect blood. It has the capability to alter the color of blood, and the contrast is enhanced by the white foam it produces, making it useful for detecting blood on dark or difficult-to-see surfaces. However, hydrogen peroxide is not practical for detecting small bloodstains because it cannot detect minute amounts of blood. Infrared imaging is an effective technique for detecting bloodstains on black surfaces, and it can detect even the smallest traces of blood. Luminol is widely employed as one of the most prevalent techniques for blood testing. The phenomenon of light emission is observed when a solution containing luminol (also known as 5-amino-2,3-dihydro-1,4-phthalazine-dione or 3-aminophthalhydrazide) and hydrogen peroxide is applied to dried bloodstains(7). Upon reacting with haemoglobin, luminol emits a blue-tinted chemiluminescence (light) in the absence of external light(7). Luminol has demonstrated efficacy in detecting blood covered with many layers of paint and can even identify blood in damaged samples while preserving DNA. Due to its high sensitivity, luminol is the most practical blood testing method. Nevertheless, the outcomes of luminol testing can be influenced by factors such as age of luminol, its preparation, storage conditions, and the technique used for chemiluminescence measurement, which may result in inconclusive or unsatisfactory findings. In a particular study, it was discovered that even blank samples emitted low levels of chemiluminescence. Further research holds the potential for developing a more cost-effective, sensitive, and reliable identification technology (4,8).

**Types of Blood Stain Patterns**

According to research, bloodstains can generally be classified into seven categories: passive, projected, impact, arterial spurt, cast-off, wipe patterns, and transfer bloodstains. Each category provides valuable information to investigators about the events that led to the bloodshed (2).

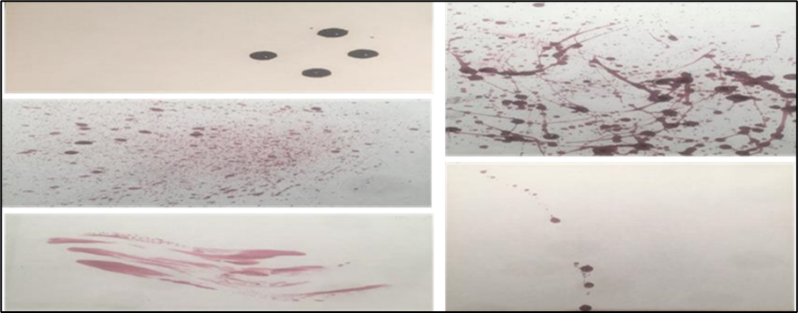


Fig.-1: Frequently encountered types of blood spatter and transfer observed(4).

In Fig. 1 (Top Left) Low-velocity drops caused by gravity can be readily distinguished by their round and smooth edges. (Left middle) A thin mist of blood, usually as a consequence of gunshot wounds, produces high-impact velocity spatters. (Left bottom) Swipes are a type of bloodstain that can result from various factors, including contact with hair and hands. (Bottom Right) A blend of big and tiny drops arises from blunt-force injuries in medium-velocity impact splatter. (Top right) Medium-velocity spatters are often accompanied by cast-off blood patterns due to the blunt-force impact. Cast-off occurs when blood flows off a murder weapon, like a hammer or bat(4).

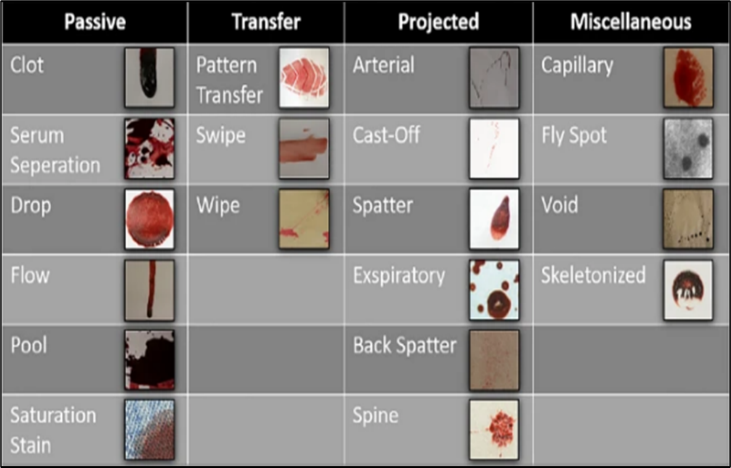


Fig.-2: One of the prevalent classification systems for bloodstain patterns that distinguishes between passive, transfer and projected traces created actively. Traces that are challenging to categorize are placed in miscellaneous category (9).

During the scrutiny of bloodstain patterns on the hands, the forensic examiner attaches crucial significance to impact spatter. When blood is impacted, it can generate either forward or back-spatter stains, as the force causes the blood to break into smaller droplets. Back-spatter patterns occur during shooting incidents when blood droplets are expelled from the entry wound and impact the front areas of the trigger hand, weapon, and supporting hand. These spatter patterns are classified as "medium to high velocity spatter." Rounded spatter marks are created when droplets impact a surface perpendicularly, while elongate marks, and "exclamation stain," occur due to low-angled impacts (10).

**Examination Methods and Computerized Analysis Reliability**

BPA, a specialized discipline, focuses on examining bloodstains discovered at crime scenes involving violence. The application of force on a body causes blood to fall passively, leading to the creation of spatter marks. In 1895, Dr. Eduard Piotrowski from the University of Krakow in Poland conducted the pioneering and systematic study on blood spatter. He used white sheets and dead rabbits to conduct experimental research and concluded that bloodstain patterns often reflect the second strike, not the initial blow. This led to further studies in BPA (11,12). The image analysis approach offers an automated alternative that can potentially be utilized at crime scenes. Professionally educated forensic specialist can analyse individual blood spots using a well-established but exceedingly time-consuming procedure. Upon impact, this procedure computes the body's 2nd dimension position on the floorplan. Comparison trials were conducted to confirm the algorithm's accuracy(13)

(10) analysed the bloodstain patterns on the deceased's hands, the position and orientation of the hands, and consequently the firearm, were determined. For this purpose, blood spatter stains on the hands were directly examined at the scene in five suicide cases involving gunshots. Close inspection of the spatter markings provided forensically relevant findings about forensic reconstruction in all cases. Hence, in shooting incidents, it is recommended to investigate and document blood-spatter findings on the hands before examining them for gunpowder residue or preparing them for transportation.

Researchers conducted a study to explore the attributes of aerosols of blood generated during physiological experiments. The participants exhaled small aerosols under various conditions, such as through straws, spitting, and making mouth sounds. Additionally, the study involved a semi-prone participant spitting through a haemorrhaging mouth or snorting through single nasal orifice. Each action resulted in the production of numerous droplets of varying sizes, with the majority being less than 1 mm in diameter. The characteristics of exhaled aerosol of blood are elucidated by utilizing the fluid mechanics and the established mechanics of airflow-induced aerosol (14). The study of formation of blood aerosol in different situations will in turn help in knowing cause of blood spatter pattern in medicolegal cases. In a study saliva test methods were compared to know the suitable method for identifying coughed or spat out blood spatter. Among the various test kits used for stain identification, the RSID (Rapid Stain Identification)-kit demonstrated the highest sensitivity and remained unaffected by the presence of blood, even in cases where saliva was mixed with blood. However, The RSID-Saliva test results for detecting saliva in blood must be interpreted within a 10-minute timeframe. Both the starch gel diffusion method and the Phadebas sheet exhibited low sensitivity, and the testing process was time-consuming (15).

(16) formulated a theoretical model to anticipate and comprehend blood-spatter patterns that occur as a consequence of a gunshot. The occurrence of rearward spatter of blood is associated with the Rayleigh-Taylor instability in blood expelled into the surrounding air. This enables the assessment of the initial distribution of sizes of drops and velocities. The movement of multiple droplets in the air is examined by employing governing equations that consider the gravity and air drag. The model's forecasts are compared with experimental data concerning back spatter generated by a gunshot impacting blood soaked in sponge.

In BPA, the analyst might need to make estimations regarding whether a particular stain over a fabric originated from a specific location, serving investigative purposes. Experiments have demonstrated that the maximum distance a blood droplet can travel exhibits significant variation, ranging from under 1 meter to over 10 meters. It is recognized that interpreting stains on porous materials, like textiles, is more challenging compared to stains on non-absorbent surfaces due to the presence of wicking. Various fluid dynamic spatter tests have been conducted and a fluid dynamics model has been developed to characterize blood droplet trajectories. The tests were carried out using pig blood, which has well-understood properties. Upon comparison, the experimental results were found to align with the numerical predictions, demonstrating agreement between the two. The findings are displayed in a chart applicable to crime scene reconstruction, designed for user-friendliness and requiring only basic knowledge of fluid dynamics to interpret effectively (17)

Cast-off splatter patterns are recognized by linear trails of circular stains. These unique patterns emerge when centrifugal forces expel droplets from a swinging object coated in blood or another liquid. In this paper, a technique for reconstructing swing or movement of the object is introduced. The method relies on Euclidean geometry and stain analysis, incorporating a three-dimensional statistical probability zone to depict the reconstructed swing. Reconstruction method can reconstruct multiple intersecting or adjacent swings, as demonstrated by simple numerical examples. The study also assesses the reconstruction method's robustness, spatial convergence, and computing time (18).

Under laboratory circumstances, an experiment was undertaken to better understand blood stain production using Awlata dye on university grounds. The researchers employed Awlata (Alta), an Indian dye commonly used for womens, to create synthetic bloodstains. This allowed them to gain insights into the formation of bloodstains at various heights and their connection to spines and satellite stains. As a result, a link between the production of blood stains and height was discovered. This discovery utilizing fictitious blood stains might aid future research (1)

**Future Advancements**

In the study, researchers examined the precision and consistency of origin estimation by utilizing the FARO (Frasier and Raab Orthopaedics) Scene program and the FARO Focus3D laser scanner. They generated five impact patterns for each of three combinations of distances from the floor (designated as z) and the front wall (designated as x). A total of fifteen spatters were generated using a custom impact rig, and subsequently, they were scanned with the laser scanner, photographed using a DSLR camera, and processed with the Scene software. This method was found to be accurate and reproducible, with results comparable to those produced by other digital software. Determining the point of origin of an impact pattern is a crucial aspect of crime scene reconstruction (19). A novel approach is formulated to enhance the accuracy of determining the area of origin. Traditionally, it is based on the assumption of straight trajectories for spattered drops, lacking a precise method to evaluate the level of uncertainty in the resulting X, Y, and Z coordinate estimation. The research focuses on addressing these two issues. The newly developed method incorporates principles from fluid dynamics and statistical uncertainty. The study's spatter patterns are accessible in a high-resolution open-access dataset, enabling comparisons with various reconstruction or stain selection approaches to the one described in this research (20).

A study has proposed a patented technique for dating drying blood pools for forensic applications. This technique is based on the morphological changes that occur in the blood pool as it dries. The study also discusses the evaporation process of gels, which exhibit similar disordered fracture patterns to blood. The objective is to identify dependable patterns capable of offering insights into the evolution of a blood pool over time. An empirical model is formulated, establishing a connection between the final dried blood patterns and the mechanism responsible for their creation. This model holds potential significance in the field of forensic bloodstain pattern analysis. Additional investigations are necessary concerning pools of diverse shapes and sizes, considering the effects of drying at various temperatures and humidity levels. The research could lead to the development of a model for blood pool evaporation, which could be used to track the drying front on a crime scene using a reference table(6). Raman spectroscopy offers a non-invasive method for analysing bloodstains and detecting specific kinetic changes in aged bloodstains for a period of up to two years. A novel classification modelling approach was utilized to initially distinguish bloodstains as blood rather than any other bodily fluid. The overall success rate for correctly identifying all stains as blood was 89%, and there was a perfect 100% identification of blood for stains aged up to one month. The spectral changes observed over time were in line with well-known biochemical processes that naturally occur as blood ages. These differences were significant enough to enable differentiation and predictions of time-since-deposition on a time scale ranging from hours to years(21)

Automated methods are gaining traction as a prominent research focus in the domain of forensic science. In a particular study, it was revealed that 20% of blood pattern analysts made erroneous identifications when tasked with identifying a blood spatter. Nonetheless, it was evident that the majority of analysts who made incorrect identifications were inexperienced and had limited training or expertise in bloodstain pattern analysis. Although professionals may not be immune to errors, there is a distinct correlation between expertise and accuracy when identifying blood spatter. Mistakes in recognizing blood spatter evidence are prevalent when the crime scene exhibits overlapping stains, rendering each individual stain challenging to differentiate (22,23). Automated method has been developed to classify bloodstain spatter patterns into two categories: gunshot and blunt impact. This approach employs machine learning techniques to categorize the data and relies on a dataset of 94 publicly available blood spatter patterns. In the study, a random forests approach was utilized to determine the most influential features for classification. The findings indicated that classification accuracy declines as the distance between the blood source and the target surface increases. At distances of 30 cm, the model attained a remarkable accuracy of 99%. It demonstrated a slightly lower accuracy of 93% at distances of 60 cm and 86% accuracy at distances of 120 cm. The presence of the muzzle gases can also affect classification accuracy, as shown by results from ten additional backspatter patterns (24). The examination featured a specific case study in which a man experienced a shooting incident followed by decapitation, resulting in a varied assortment of blood spatter patterns. These patterns encompassed high-velocity impact spatter from the bullet, arterial spurts arising from the decapitation, and low-velocity drips and smears indicative of dragging. Due to this, crime scenes can exhibit a combination of various blood spatter types. In one study, an image-processing method was employed to differentiate blood spatter into local and globular components, assigning each a distinct numerical value. In the future, statistics could be employed to promptly differentiate between different bloodstain patterns based on this data, but further research is required to explore additional types of blood spatter. Another method that allows analysts to examine more accurate and detailed crime scene images is multi-resolution 3D scanning(22,23).

**Discussion**

In the field of bloodstain pattern analysis, the crucial task is to determine the source and properties of bloodstains, as this plays a vital role in comprehending the events that transpired at the crime scene. Nevertheless, conducting a comprehensive analysis of the entire crime scene for the presence of blood is impractical. Therefore, the ABC Approach (Appearance, Behaviour, and Context) is employed as a valuable tool to concentrate on potential bloodstains that require verification(4). To examine bloodstains, first, we must detect if they are indeed blood. The Kastle-Meyer test detects haemoglobin but risks DNA destruction. Hydrogen peroxide is cost-effective and doesn't interfere with DNA but has limited sensitivity. Luminol is highly sensitive and widely employed, detecting minute traces even in low-light conditions(5,6).

Categorizing bloodstains into passive, projected, impact, arterial spurt, cast-off, wipe patterns, and transfer types provides vital data for reconstructing crime scenes(2). Forensic examiners give particular significance to impact spatter patterns when investigating bloodstains on the hands of shooting victims(10). It is recommended to prioritize examining and documenting blood spatter patterns on hands before checking for gunpowder residue or transporting evidence(10). Understanding exhaled blood aerosol characteristics is essential for interpreting spatter patterns in medicolegal cases. Fluid mechanics and airflow-induced aerosol mechanics knowledge help determine the origin and pattern of blood spatter in forensic investigations(14). The RSID-kit shows high sensitivity in detecting coughed or spat-out blood spatter, remaining unaffected by blood presence, even with saliva mixed in. Interpret RSID-Saliva results promptly within 10 minutes. However, the starch gel diffusion method and Phadebas sheet exhibit low sensitivity and are time-consuming(15).

Interpreting bloodstains on porous materials like textiles poses wicking challenges. Fluid dynamic spatter tests resulted in an accurate model for blood droplet trajectories, aiding crime scene reconstruction. Experimental and numerical results validated the model's effectiveness(17). A user-friendly chart based on these findings helps investigators interpret blood spatter patterns effectively with basic fluid dynamics knowledge(17). Cast-off splatter patterns, recognized by linear trails of circular stains, indicate droplets expelled from a swinging, blood-coated object. Euclidean geometry and stain analysis reconstruct the object's swing or movement, enhancing crime scene analysis(18).To study bloodstain formation at different heights and their relation to spines and satellite stains, researchers used Awlata (Alta), an Indian dye simulating synthetic bloodstains. This experiment revealed a connection between bloodstain production and height, opening avenues for further research with simulated bloodstains(1).

FARO Scene program and FARO Focus3D laser scanner show an accurate and consistent origin estimation, comparable to other digital software(19). A proposed patented technique for dating drying blood pools in forensics has significant potential, establishing a connection between final dried blood patterns and their creation mechanisms(6). Further investigations should explore pools of different shapes and sizes, considering drying effects at various temperatures and humidity levels. This research could lead to a model, aiding crime scene investigations with a reference table to track the drying front(6). Raman spectroscopy offers a non-invasive approach to analyse bloodstains and detect specific kinetic changes in aged bloodstains for up to two years(21). A novel classification modelling approach effectively distinguished bloodstains from other bodily fluids with an 89% overall success rate. For stains aged up to one month, blood identification was 100% accurate, showing great potential for enhancing forensic investigations' efficiency(21). Automated methods are gaining momentum in forensic science research, aiming to improve accuracy and efficiency. One study found that 20% of blood pattern analysts made erroneous identifications when identifying blood spatter(22,23). To address this, an automated machine learning method was developed to classify bloodstain spatter patterns into two categories: gunshot and blunt impact. Using a dataset of 94 publicly available blood spatter patterns, this approach achieved remarkable 99% accuracy at 30 cm distances between the blood source and target surface(24). In another study, an image-processing method differentiated blood spatter into local and globular components, assigning distinct numerical values. Statistics could promptly differentiate between various bloodstain patterns based on this data, showing promise. Further research is needed to explore additional types of blood spatters(22,23). Multi-resolution 3D scanning offers valuable crime scene images for accurate analysis. This technology provides a comprehensive perspective, enhancing the understanding of blood spatter patterns(22,23).

In conclusion, BPA forms an essential role in criminal investigations, offering invaluable insights into the events surrounding bloodshed (1,10,17). By examining the size and arrangement of blood spatter stains, BPA can assist in establishing the positions of individuals involved in a crime scene, the type of weapon utilized, and distinguish between various incident types, including accidents, homicides, and suicides. The integration of cutting-edge digital software, such as the FARO (Frasier and Raab Orthopaedics) Scene program and 3D imaging techniques, has primarily augmented BPA's capabilities in recent times (20). The studies related to blood aerosols formed in various situations will help in finding cause of Blood spatter pattern. Although considerable strides have been made in qualitative and quantitative BPA utilizing image processing and computerized methods, there remains a necessity for further exploration and validation of automated approaches(22). Additionally, research efforts should be directed towards refining methods for dating dried blood to enhance the temporal accuracy of crime scene reconstruction using BPA (13). Establishing of reliability and precision in the mathematical models for BPA with help of further research is essential to bolster their applicability in forensic investigations. With the relentless advancement of technology, the future of BPA holds promising potential, especially within the realm of digital platforms. Uninterrupted research and development endeavours will assuredly refine and broaden BPA's scope, yielding even more comprehensive and precise outcomes in crime scene analysis. In essence, the study of bloodstain patterns continues to evolve as a dynamic field with ongoing prospects for progress and innovation.

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