

# Data Visualization of Graph-Based Threat Detection System

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**Abstract.** The Activity and Event Network Model (AEN) is a new security knowledge graph that leverages large dynamic uncertain graph theory to capture and analyze stealthy and long-term attack patterns. Because the graph is expected to become extremely large over time, it can be very challenging for security analysts to navigate it and identify meaningful information. We present different visualization layers deployed to improve the graph model's presentation. The main goal is to build an enhanced visualization system that can more simply and effectively overlay different visualization layers, namely edge/node type, node property, node age, node's probability of being compromised, and the threat horizon layer. Therefore, with the help of the developed layers, the network security analysts can identify suspicious network security events and activities as soon as possible.

**Keywords:** data visualization, security, intrusion detection system, intrusion prevention system.

## 1 Introduction

In the network security domain, analysts deal daily with network packets and security events and alerts generated through a various data sources such as firewalls, intrusion detection systems (IDS), intrusion prevention systems (IPS), system logs, etc. With an exponential increase in the amount and diversity of security data, there is a growing demand for visualization tools to help with analyzing the data and gaining insight into it. Visualization tools help avoid having to spend excessive hours on raw data analysis and allow the security analysts to distinguish unusual patterns and trends in even the most intricate data sources. This will let analysts identify the existing and novel network attacks in the minimum required period. Knowing that the visualization requires data from single or multiple sources, either one or many of the below data sources can be input into the system. Network traces, security events (IDS, IPS, Firewalls, AV), network events (switch, router, or server data), or application logs are some instances of the data sources [1]. It is needless to say that, with an increase in the incorporation of data sources to be fed to the visualization system and their features, the network security analyst's ability to gain insight into irregular traffic trends and events also improves. The remaining sections in this report are structured as follows. Section 2 gives

an overview of existing security visualization models and gives a summary of key features of the AEN system architecture. Section 3 outlines the proposed model to address previously stated limitations. Section 4 depicts the experimental evaluation of the proposed scheme. Section 5 makes concluding remarks.

## 2 Related Work

Shiravi et al. [1] reviewed network security visualization practices by classifying them into five classes, host/server monitoring, internal/external monitoring, port activity, attack patterns, and routing behavior. The first visualization class in this study is host/server monitoring which mainly exhibits the nodes in the network as hosts or servers and tries to identify possible correlation among them with the aim of detecting the malicious nodes. One of the earlier works that was done on small-sized networks in this class was authored by Erbacher et al. [2],[3] where they placed the monitored server in the middle of the visualization layer, and the rest of the hosts are around five concentric circles where each node's ring defines a distinct IP address from that of its monitored server. In [4], Takada and Koike developed a model called Tudumi. Tudumi is a 3D visualization model to observe and examine the user performance on a server, achieved by the utilization of multilayered concentric disks in a small-sized network. To highlight various access techniques such as file transfer or terminal service, this model uses different-sized dashed lines. A model developed by Lakkaraju et al, called NVisionIP [5]-[6], focuses on large networks presented in a grid of 256 by 256, where each of the cells displays the hosts' associations. The horizontal axis of the network represents the network subnets, and the vertical axis of the network represents the subnet hosts. There is a magnifier that enables the analyst to access the nodes of interest in the network. To detect the hidden malware in the network, Fink et al. [7] developed a model which illustrates the correlations between network traffic and host processes. VISUAL [8] is a security visualization system developed to permit the analyst to observe the interaction patterns between an internal network regarding external sources. The internal network is a grid, where each cell represents one of the internal hosts. On the other hand, external sources are depicted out of the internal grid, with the square dimension indicating the activity level. VizFlowConnect [9] employs parallel axes to display the current relations among network nodes in the network, which is achieved by designing three parallel axes. While most left is responsible for nodes originating network transfer to the internal network, the center is responsible for presenting the internal hosts, and the right one is responsible for depicting the destination nodes of internal traffic. The port activity visualization class has been designed to highlight the viruses, trojans, worms, and zero-day exploits activities. The developers of this visualization class believe that with the scaling techniques implemented due to the amount of traffic and extended range of possible port numbers and IP addresses, the malicious actors can be located. Abdullah et al. [10] designed a port-based

sketch of activities in the network based on the given services. It is discussed that by assigning popular ports to principal services, the chances of exposing them to attacks rise. Therefore, they are grouped in bins of 100's, whereas the registered ports are grouped in bins of 1000's, and the rest of the private/dynamic ports are assigned in a single bin. This system provides the ability for the user to view more precise aspects of the irregular activities in the network by depicting the data over time. Potential Doom, a system proposed by Lau [11], involves the rotating cube, which attempts to visualize the coarse trends in large-scale networks, namely port and IP data in a 3D cube, with each axis of three-dimensional representation as a component of a TCP connection. The X-axis represents the destination IP addresses, Y-axis represents the port numbers, and Z-axis represents the source IP addresses. The system is suitable for single attacks and can only be employed for the discovery of port scans. In [12], McPherson et al. present ProtVis which uses a 256x256 grid of various colors to reflect the network activities on grid cells. The port's position on the grid is decided by separating the port number into an (X, Y) position, where X highlights the port number's high byte and Y highlights the port number's low byte. Through time, each point's changes are depicted using a distinct color, where black indicates no change, blue indicates small change, red indicates larger change, and white indicates the most variations. In addition, the system provides a magnifier to support more specific data regarding specific ports. One of the challenges the system faces regarding identifying malicious nodes is when irregular activity is discovered between ports with high and legitimate activities. The attack patterns visualization class targets both detection and presentation of attacks in different steps. This type of visualization is of prime importance, because various attacks behave differently and many of them are implemented in multi-steps, including reconnaissance, scanning, gaining access, maintaining access, clearing tracks, and installing back doors for future access. Because the high number of alerts generated daily by the intrusion detection systems is at times overwhelming for the security analysts, they constitute one of the well-known sources of data for this class. Girardin [13] proposed an unsupervised machine learning system developed with detecting the network's irregular and intrusive actions in mind. The system depicts network state and deviations from natural behavior by using front ground and background colors, size, and relevant positioning on a map. In this way, similar events are grouped, and the map is also arranged in the same way. Nyarko et al. [14] developed NIVA, a network IDS visual analyzer. It utilizes data from multiple intrusion detectors and uses links and colors to manifest attacks. The system includes a GUI window and a 3D rendering window which consists of glyphs connected by links. The position of each glyph depends on its IP address, meaning that closer glyphs favor closer IP addresses. Colitti et al. developed BGPLay [15], a system which permits ISPs to observe the reachability of a specific prefix from the viewpoint of a given edge router while including animation to specify routing

adjustments. Wong et al. [16] developed the TAMP system to visualize the BGP irregularities by employing statistical techniques to perform BGP data aggregation. They proposed animation techniques to depict the routing behavior variations over time to assist the network administrators in identifying any abnormal patterns. The principal objective of the AEN system is to assist network analysts in detecting any security irregular patterns or malicious nodes. The system functions by utilizing the raw data from various network nodes and external repositories to discover the current node-to-node relationships and extract unusual ones. Multiple data sources such as network packets, system logs, and intrusion detection alerts are processed to generate the graph.

### **3 On the AEN Graph Model**

#### **3.1 Overview of the AEN Graph Model**

The AEN Graph is a new security knowledge graph model developed at the Information Security and Object Technology (ISOT) Lab to capture and analyze stealthy and long term attack trends and patterns. To capture the inherent uncertainty and dynamic nature of network environments and attack occurrences, AEN consists of a dynamic uncertain directed multigraph model. The graph engine is developed using emerging graph database technologies because one of the requirements of the model is the need to load the entire graph in memory for malicious patterns detection and analysis. The graph model is updated continuously and maintained over time, with most of the historical information being preserved by necessity and leveraged in long-term attack detection. As a result, over time the graph is expected to become extremely large in size. The main concern in the graph construction is the method employed to mine different data features responsible for nodes identification, their relationships, and attributes. The mining method can be implemented by 1) direct connection to the data source or 2) from the available data gathered from various tools and services, or 3) by data mining into aggregates, or 4) from the previously known attacks by security experts, or 5) from log analysis performed on the known network applications and service calls to or from the mentioned applications and data sources such as hypervisor logs, syslog, and IDS alerts. Another input category is attack fingerprints, which are not automatically generated by the system and developed by security experts from past attacks. Even without this type of data, the system can leverage attack signatures indirectly through its IDS alerts. However, these fingerprints provide an additional layer of information to the model in the form of a database of well-known attacks that can help the identification by better incorporation into the model.

### 3.2 Graph Definition

To understand how the graph is constructed, we must analyze the features mentioned above to determine distinguishable characteristics. To begin with, it is worth considering how each feature can be used to model the network. As a sample, IP address-domain names relationship can be considered. Graph nodes represent the features, and the edges represent their relationships. However, features such as protocol and port are better utilized as relationships' descriptors and therefore are employed to characterize attributes of either nodes or edges. Generally, the AEN model's nodes are interpreted by any feature for which valuable relationships can be formed, and the edges are constructed based on those relationships and their direction. The rest of the features can be utilized to describe attributes of either nodes or edges. It is important to note that the model is confident in identifying or in the correctness of the extracted information from the features. For instance, when related TCP handshake packets between two nodes are received, the model is confident that the hosts are communicating and in which direction. However, it is worth noting that the IDS alerts and graph operations such as pruning, chaining, decaying, and clustering are inherently imperfect. That adds a layer of uncertainty to the nodes, their relationships, and their respective attributes. Ultimately, as there are continuous changes in the system and a constant demand to track the network entities and their relationships, the model requires to maintain the information on the periods in which each element has existed to identify the vital chronological relationships. In summary, below are the characteristics of the graph model. 1) Processing times/latencies are negligible. 2) Through time, nodes, edges, and their attributes vary and have a lifetime. 3) Nodes have their attributes and are labeled. 4) Nodes can have various relationships at the same time. Consequently, nodes can have various edges connecting them. 5) Relationships have a source and a destination. Therefore edges are directed. 6) Relationships have their properties. Thus edges are labeled. 7) Both relationships and nodes can be uncertain. Thus nodes, edges, and their attributes are weighted by probabilities of existence.

## 4 Proposed Visualization Model

To address the visualization challenges discussed, many layers have been developed. The implementation is performed via Javascript programming language, and with the help of vis.js library. As previously mentioned, by feeding the raw data collected from the network logs to the system, the graph is constructed. The system before the implementation of any visualization layer is depicted with all nodes represented as grey ovals and all edges as grey arrows without any labels in the zoom-out view versus with the labels in the zoom-in view. To integrate different visualization layers to the model, a distinct tab named node view, is designed in order to provide the capability of viewing the network elements based on the type of nodes, type of edges,

property, node age, probability of compromise and threat horizon. In addition, a distinct layer is designed to show or hide the labels.

#### 4.1 Element Type Layer

The initial visualization layer developed provides the ability to filter network elements based on their types. There exists a checkbox named ‘Show/Hide Labels’ that enables the end-user to view the network nodes with or without the labels. Besides, when the user selects not to include the label in the graph, all the nodes would be depicted as same-sized circles. This layer functionality consists of the different node/edge types and the node properties. The node type category includes HOST, DOMAIN, ALERT, IP, ORGANIZATION, and LOCATION that provide the relative information. Upon selecting each type, the nodes belonging to that specific category are colored while the rest of the nodes are grey. In addition to node types, different types of edges have been added to this layer, including AUTH\_ATTEMPT, TRIGGER\_USED, IP\_LOCATED\_AT, PART\_OF, RESOLVED\_TO, CONTROLS, LOCATED\_AT, OWNS, SESSION, ALERT\_TRG\_BY\_HOST. Upon selection of edges, the user would again observe them in color and the rest of the network elements in grey. Thanks to different layers operating together, selecting different types of nodes and edges is possible. It gives users a better understanding of network elements. Another function of this layer is its ability to demonstrate the malicious nodes in red color. Figure 1 is an example of a malicious node highlighted in red when selecting the malicious property checkbox. In conclusion, this layer provides the ability to show/hide all the labels and all or some of the network elements based on their node type or edge type, or node property in color.



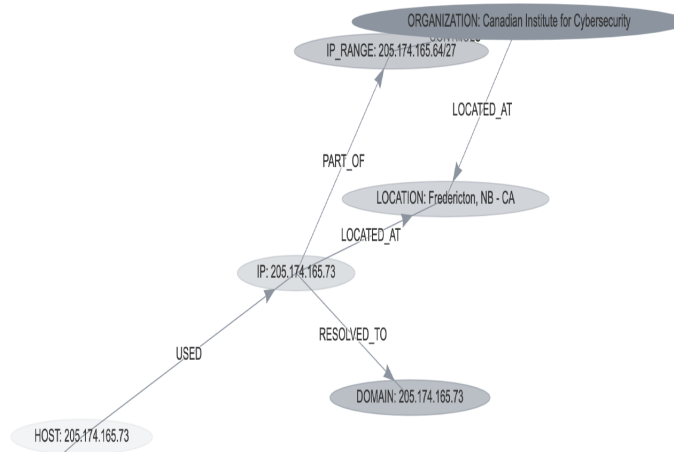
**Fig. 1.** Malicious Property

## 4.2 Node Age Layer

One of the key characteristics of the AEN model is its dynamic nature. Nodes and edges are added continuously as more data arrive. Timestamps are associated with the graph elements to convey their age. The functionality provided by this layer mainly concerns the age of each node in the network. It was uncertain how far in time each specific node has been added to the graph or updated in the graph (for instance two days ago or three days ago). The visualization of this layer has been implemented with the aid of the opacity feature. Opacity can have a value between zero and one that means if the node is added or updated more recently, say two days ago, it is of higher opacity than the nodes added or updated four days ago. When the related node and age data come from the back-end of the system to the front-end, the required properties are extracted, the timestamp, in this case. The node's age is computed based on the timestamp. It is noteworthy that the age limit is ten days and the nodes which are added/updated before that time are shown with the same opacity. The opacity is calculated based on below formula.

$$\text{Opacity} = (1 - (\text{age}/10))$$

Figure 2 represents an overview of the network elements when this layer is selected. As part of this layer's functionality, it is possible to choose it together with other layers such as the node's type layer to merge the opacity with the nodes/edges colors.



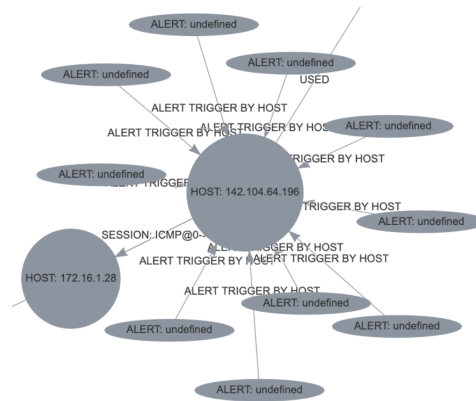
**Fig. 2.** Node Age visualization layer

### 4.3 Probability of Compromise Layer

This layer illustrates the nodes based on their probability of being compromised. The graph engine assigns the probability and shows that a specific host is malicious or is compromised, by considering all the detectors together. The probability of being compromised is a value between zero and one fetched from the backend. After the comparison is performed, the size of the nodes of the probability of compromise category is computed based on the below formula.

$$\text{size} = \text{Int}(100 + \text{node.prob\_c} * 30)$$

Where prob\_c denotes the probability of compromise. Figure 3 depicts the graph nodes with a higher probability of being compromised as larger objects while the rest of the nodes as smaller objects.



**Fig. 3.** Probability of being compromised

### 4.4 Threat Horizon Layer

Threat Horizon is defined as the set of all possible nodes with which a node 'u' could have exchanged data. As a result, the data exchange ultimately affected them, directly or indirectly. In practice, if node 'u' is malicious or compromised, the set of nodes which 'u' could have been in contact with are also compromised, or at least been targeted. More formally, two underlying concepts must be defined [17]: (1) Journey, which is a "time-respecting walk" through a path over time, that is, a walk through a path between 2 nodes 'u' and 'v' over time such that each edge is traversed in chronological order and such that each edge existed at the point in time it was traversed; (2) reachability of 2 nodes 'u' and 'v', which is defined



as the existence of a Journey between nodes ‘u’ and ‘v’. Then we can define the Threat Horizon of node ‘u’, ‘TH<sub>u</sub>’ in short, as the set of all nodes in a graph ‘G’ reachable from ‘u’. Figure 4 depicts the threat horizon, and the node clicked to show the threat horizon is called the focal point. The hosts that become orange upon selecting the focal point are the nodes that had direct or indirect communication with it. If the focal point is malicious (which is not necessarily the case), then there is a chance that the focal point host could have compromised the hosts inside the threat horizon.

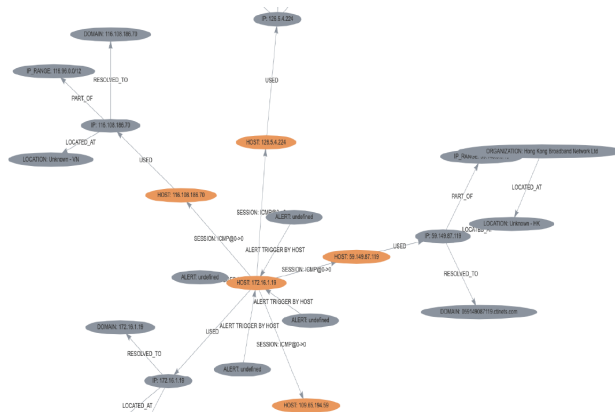
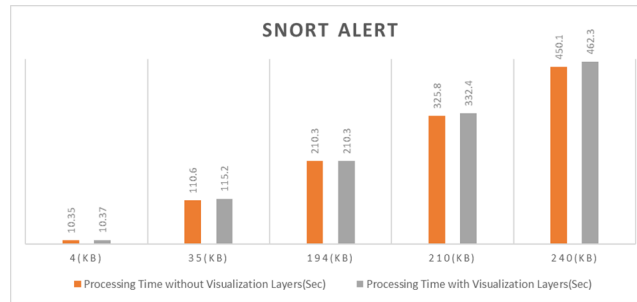


Fig. 4. Threat Horizon layer

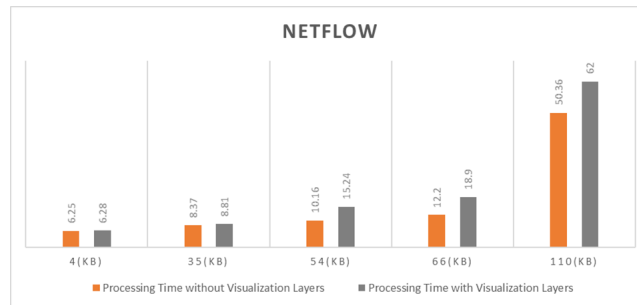
## 5 Performance Evaluation

The response time and CPU utilization are used to evaluate the performance of AEN graph visualization layers. We have used different sizes of snort alert and the netflow files to determine the size of the graph. Snort is one of the IDS used among the data sources. Netflows are aggregate packets, also part of the data sources. The evaluation was run on a Dell 2.6 GHz Core i7 (6 cores) and 16GB of memory. The response time and the CPU utilization are studied to measure the scalability of the developed layers. Each file is input into the system five times, and the average output values are computed for the response time and CPU utilization. The response time is the time duration over which the graph is loaded to the system, and the time the graph appears on the canvas. The average response time is measured in terms of seconds. The CPU utilization indicates a computer’s processing resources or the volume of work handled by a CPU. The actual CPU utilization differs based on the amount and type of managed computing tasks. Specific tasks require heavy CPU time, while others require less because of non-CPU resource

requirements. CPU Utilization is measured in terms of the unit ms. Figures 5 and 6 depict the response time of different sized snort alert and netflow log files fed to the system before the activation of visualization layers. As observed in the graph, the response time increased as the file size enlarged. To handle larger capacity, more computation power would be required, like by using powerful server machines on the cloud. The same experiment was again conducted with the visualization layers to be able to compare the performance before and after the visualization layers activation. As shown in Figures 5 and 6, the response time has changed in terms of 2 milliseconds to 12 seconds depending on the file sizes compared to before, which can be interpreted as the hardware limitations.



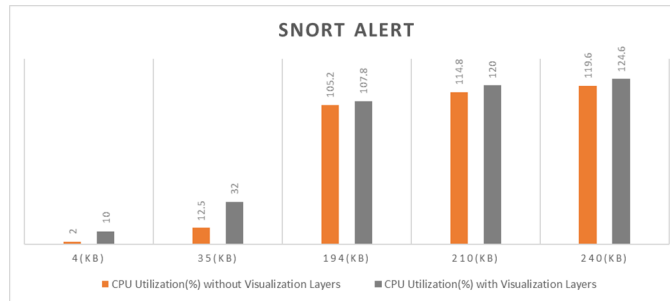
**Fig. 5.** Response time of the different sizes of snort alert file with vs without visualization layers



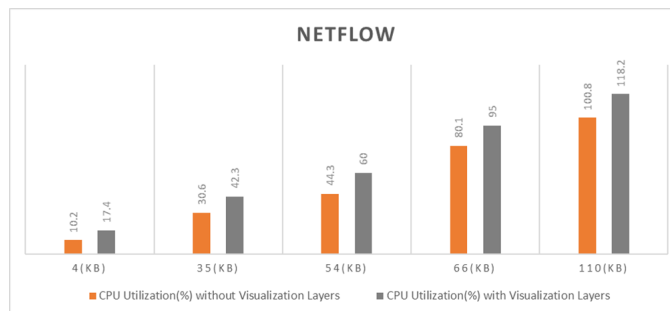
**Fig. 6.** Response time of the different sizes of Netflow file with vs without visualization layers

Furthermore, the same experiment has been run on networks of different sizes to measure the CPU utilization of the system. As expected, the system utilization increases with the size of the network. For the files less than 100 KB, the CPU utilization is acceptable, but as the size of files grows to 194 KB that contains hundreds of nodes, the system utilization also increases to the more than 100%. As

mentioned before, the system on which the experiment is conducted is a multi-core computer where the CPU performs significantly better than a single-core CPU of the same speed. Multiple cores not only allow PCs to run multiple processes simultaneously with greater ease and increasing the performance when multitasking but also provide the possibility to have more than 100% utilization depending on the number of cores available on the system. Again, as mentioned above, it is recommended to use computers with higher configuration capabilities to be able to load higher data rates and fully utilize the features provided by the AEN system model. In addition, Figures 7 and 8 depict the average CPU utilization after the activation of visualization layers and as expected the CPU utilization increased by a range of 8% to that of 20% comparing visualization version to no visualization version in different input file sizes.



**Fig. 7.** CPU Utilization of the different sizes of snort alert file with vs without visualization layers



**Fig. 8.** CPU Utilization of the different sizes of Netflow file with vs without visualization layers

## 6 Conclusion

In this paper, many visualization layers were developed to enable the security analysts to have a high-level view of the ongoing network activities. Different visualization layers include the following. Show/Hide Labels checkbox allows the end-user to view the network nodes with or without the labels in addition to all the nodes in same-sized circles when the user selects not to include the label in the graph. In the element type layer, the functionality is defined by depicting the specific node/edge types and the node properties in distinct colors upon selecting each checkbox in this layer. The element type and show/hide labels can be chosen together. Node age layer depicts the age of each node (i.e., how far in time each specific node has been added/updated in the network) with different opacity levels. Node age layer can be selected along with the element type layer and the show/hide labels checkbox. Probability of Compromise Layer employs the graph engine to assign the likelihood and show if a specific host is malicious or compromised by enlarging the node. The threat horizon layer lets us see all the nodes that had direct or indirect communication with the focal point. The threat horizon layer functions with the probability of compromise and node age layers. Before implementing the visualization layers, the AEN graph model did not explicitly represent the nodes/edges that might be of interest to the security analysts. With the help of visualization layers, analysts can view the elements of interest in different colors/shapes than the rest of the nodes in the network. It enables the analysts to save time by not investigating raw data, especially as the AEN graph model is designed to be continually growing. In the performance evaluation section, the visualization layers' performance has been measured in terms of processing time. It has been observed that different layers are being loaded in a matter of ms. This time grows as the size of the files gets bigger, which is expected, and since the processing time difference for the same layers of different file sizes is 1 to 3 ms, it can be ignored. Although different visualization layers have been developed, there are still many features that can be added to the system to enhance the system's performance, such as attack progression visualization. The goal of this feature is to make it easier for an analyst to view how an attack progressed through time. In practice, that means that once an alert is generated, either via the IDS or via one of our detectors, the system should identify and highlight an attack path by using data from the alert, fingerprint, threat horizon, etc. and then, by using the graph timeline feature, correlate the attack path with the graph elements in previous and future points in time and display the attack progression from the first element to its current form. The progression here can be understood as a series of subgraphs/attack paths that show the attack as it progresses through time.

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