Next-generation Network Architecture Led by Information-Centric Networking

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The Internet was originally aimed at sending and receiving data between host computers. However, developments in recent years have led to it being used as a distribution system for information such as video and music data. There is thus a growing interest in information-centric networking (ICN), a new networking architecture that better supports information-centric Internet usage. The basic idea is that the network architecture does not depend on locations (servers) but on named data, making them directly accessible to users. Notable characteristics include more efficient data access through in-network caching, simplified content request messages for mobility support, and content-specific security functions. Many universities and corporations are utilizing this architecture and reporting advances in protocol specifications, open software, prototype systems, and so on. Although ICN is still in the research phase, there should be great promise for the future. This paper outlines the basic paradigm of ICN and describes the characteristics of the two types of ICN architecture. It also describes the current trends in the research and initiatives taken by various organizations, including the research being conducted by Fujitsu Laboratories of America.

1. Introduction

The Internet has its roots in the ARPANET project, which began as an experiment in packet-based communications among American universities and research institutions in the 1960s. From that time on, the number of host computers for making connections increased steadily, and the Internet eventually expanded into today's large-scale system. The Internet saw massive growth, particularly in the 1990s, and technology and usage scenarios continued to develop after 2000. In recent years, the Internet has come to be widely used for distributing movies, music, and other types of content. Additionally, the appearance of smart mobile devices equipped with high-performance cameras and communication functions and the growth of social networking services (SNSs) that simplify the management and distribution of user content have increased the opportunities for general users to disseminate content.

At the same time, the Internet of Things (IoT) is fast approaching as an era in which devices numbering far more than the human population will be connected to the Internet. These devices are expected to produce a huge amount of data that will flow back and forth over the network. In such an environment, the Internet is changing from playing a role centered on host-to-host communications as originally designed to one focused on delivery and distribution of information. Research on information-centric networking (ICN) suitable to this evolution in the Internet usage format has become quite active in recent years.

In this paper, we introduce the basic concept of ICN, the features of two ICN-related architectures, current research trends and activities at various organizations, and ICN activities at Fujitsu Laboratories of America.

2. ICN features and aims

Given this qualitative and quantitative transformation of the Internet, researchers have begun discussing the need for constructing a new network architecture. Such research actually began about ten years ago, centered on European and American national projects under the name Future Internet Architecture. Typical of these projects are the Data Oriented Network

Architecture (DONA), Network of Information (NetInf), Publish-Subscribe Internet (PURSUIT), Named Data Networking (NDN), and Content-Centric Networking (CCN) projects. They have a common goal of constructing an architecture centered on the delivery and distribution of information in contrast to one driven by host-to-host communications, and they are generally referred to as ICN for this reason.[1),2)]

Although about ten different architectures have been proposed for ICN, the basic idea is that network functions should operate in terms of named content instead of location (server) and that the focus should be on delivering content to users. Given a request for content from a user, a system based on one of these architectures does not specify the location from which it is to be obtained, but instead it replicates the content on multiple servers within the network system. A major advantage of this scheme is that content can be obtained from the server, possibly a nearby one, at the lowest delivery cost. This "in-network caching" function should reduce the volume of data traffic and the response times. Another advantage is ease of mobility. Since "content name" is separated from "server," the movement of a node in possession of certain content can be easily accommodated—a user can obtain that content by requesting it by name the same as the user would do before that movement.

In this way, ICN enables content to be obtained without having to consider on which server it is located. Along with this, security functions, which have traditionally been consigned to servers, should be incorporated in the data itself. To this end, authentication functions that check whether received data is the actual data requested by the user have come to be included in each ICN architecture. These functions can prevent a user from erroneously receiving different content that a third party has labeled with the same name for whatever reason. A mechanism for encrypting content in ICN is also being studied so that content is released only to specific users. Key management used in authentication and encryption is defined in all ICN architectures, most of which use a key management method that incorporates content name.

More recent expectations of ICN include improvements in system efficiency up to the service level and more efficient design of application software used in the network. In ICN, the target is "content" that is more than the bit strings handled by conventional networks and that is closer to the application software. Optimal system design in terms of both applications and the network should result from making use of these properties. The manner in which content is named is attracting interest as an important aspect of such a design. A structured scheme of content naming is needed that takes into account the structure of application software and that makes content easy to identify and retrieve. Discussions on achieving a content name design that considers realistic use cases are now taking place at ICN-related meetings.[3),4)]

At the same time, concepts such as the distributed service platform[5)] and edge computing,[6)] which are aimed at the IoT, have been proposed as a way of further expanding cloud computing, which has already found widespread use. The idea is to distribute data storage and processing throughout the network instead of centralizing it at a data center. While ICN is aimed at deploying content in a distributed manner, named function networking (NFN), a recently proposed concept, is aimed at distributing processing throughout the network and enabling it to be obtained by name. NFN is likewise being discussed at ICN-related meetings.[7)] This has led to ICN being incorporated into the idea of distributed data storage and function execution, which is being discussed within a different framework.

ICN-related research has been accelerating in the last few years, and new organizations and associations have been established one after another. For example, ICN workshops have been held since 2011 at leading international conferences in the field of networking technology, and an ICN-dedicated conference was launched at the Association for Computing Machinery (ACM) in 2014.[8)] In addition, NDN community meetings[4)] and CCNx conferences[9)] are providing tutorials on protocol and open software, exhibiting demonstration systems, and holding discussions on putting ICN on the path to deployment. In Japan, the ICN Consortium was founded in 2014, and its activities, including workshops, have commenced.[10)]

In terms of standardization activities, the Information-Centric Networking Research Group (ICNRG)[3)] was established in 2012 in the Internet Research Task Force (IRTF), a sister organization of the Internet Engineering Task Force (IETF). Present discussions are concerned with packet formats and other topics. Additionally, at ITU-T Study Group 13, use cases with respect to data-aware networking (DAN) are being discussed.

ICN architectures can be broadly divided into two types. One type uses a centralized name resolution service (NRS) and features flat naming of content. A typical example of this type of architecture is NetInf. The other type features name-based routing, in-router caching, and hierarchical naming of content. A typical example of this type of architecture is NDN. These two types of architecture were originally studied independently, but the tendency now is to implement the best features of each in the other.

3. NetInf architecture

The NetInf architecture features an arrangement of equipment for converting content names into content locations by using an NRS.[11] One method for implementing this is to establish an additional layer above the Internet Protocol (IP) layer and place the NRS on this layer for use in converting content names to IP addresses. When new content is published or content is newly cached in a node, the corresponding content name is registered in the NRS. The NRS equipment has a hierarchical structure consisting of a global NRS and local NRSs. Newly published content or newly cached content is first registered with a local NRS. Then, if a data request for that content is received from within the same local area, the content location is provided by that NRS. Information registered in a local NRS is also registered in the global NRS. A filter is used to limit the amount of information registered in the global NRS. If a data request for that content is received from another local area for which the local NRS has not yet received any information about that content, the content location is provided by the global NRS.

Since the NetInf scheme makes use of existing routers, it can be implemented with a minimal number of hardware changes. The scalability of the global NRS is a major concern if dynamic content placement is to be fully supported on the scale of the Internet. Therefore, current ICN research is focusing on the NDN type of ICN architecture, as explained in the following section.

4. NDN/CCN architecture

NDN and CCN are currently the most actively discussed architectures in ICN research.[4),9),12)] NDN is the focus of a research project spanning a number of universities in the United States, led by UCLA. Its main source of funding is the National Science Foundation (NSF), which is funded by the federal government. CCN is the focus of a project conducted by the Palo Alto Research Center (PARC), a private research institution in the United States. These two projects are currently pursuing protocol implementation and library development separately, but they originally arose from a single architecture, as described below.

NDN/CCN features two types of packet formats: Interest and Data. An interest packet is used to request content using the name of the content. A data packet is used to transport the requested content. An interest packet is routed to the node having the content with the specified name, as determined from information in a table at each NDN node, and a data packet is returned to the client along the same path. Some or all NDN nodes along the way cache the data packet in case another user requests the same content (**Figure 1**). The procedure in detail is as follows.

1) An interest packet from user A is forwarded via NDN nodes B, C, and D to server E in accordance with information in the routing tables (forwarding information base: FIB).
2) Server E sends a data packet with the requested content along the same path to user A (pending interest table: PIT).
3) NDN node D caches a copy of the content in the data packet (whether caching is performed at each NDN node on the return path depends on the operating policy).
4) An interest packet for the same content from user F is sent to NDN node C. The routing at node C points to server E, but the content of interest is discovered along the way at NDN node D (content store: CS).
5) Node D sends the data packet with the requested content along the same path to user F.

An NDN node contains three types of tables for routing or accessing cached data: FIB, PIT, and CS. The FIB establishes the correspondence between the content name or part of the content name called a prefix and Face—an extension of Interface as described

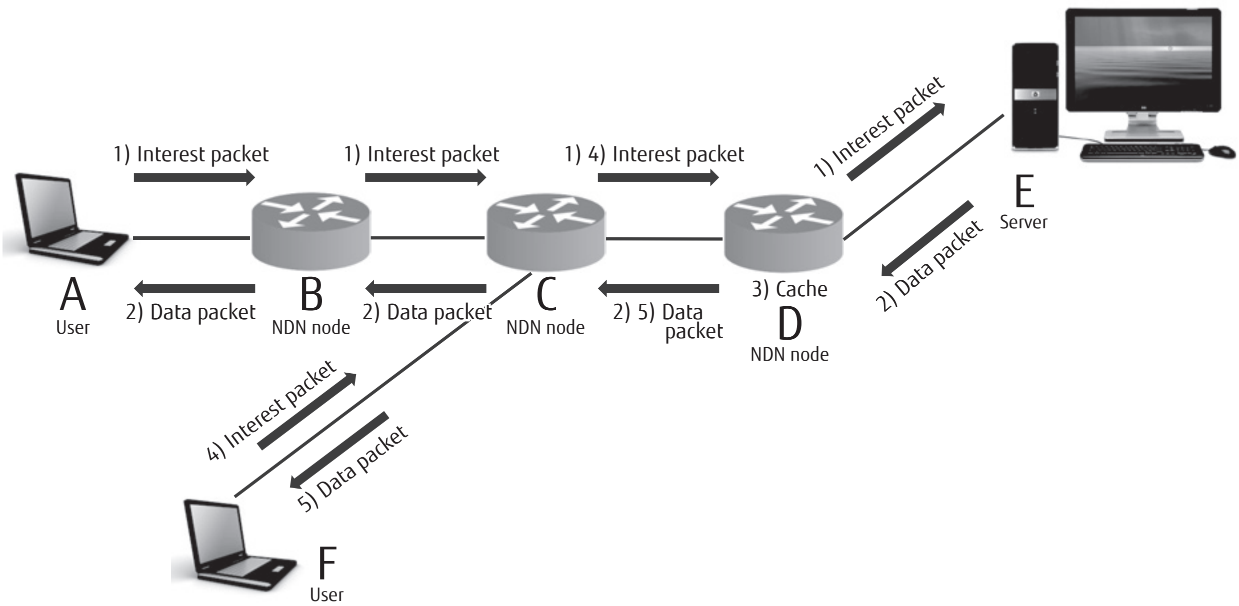


Figure 1
NDN system.

later—to enable Interest routing. The PIT is provided so that the data packet can retrace the path taken by the interest packet. During the time between forwarding of the interest packet by the NDN node and return of the data packet, the PIT records where that interest package came from in the format of requested content name and Face. The CS stores the data cached at that NDN node and the content name corresponding to that data (**Figure 2**).

Face, an extension of Interface, is used for connecting to a neighboring node in conventional routers. Envisioning a situation in which data may be transferred to various applications within the same node, this interface was given the name "Face" in NDN/CCN. In the FIB and PIT, a single content name can correspond to multiple Face entries ("Multi Face"), which can be used for more efficient content searching and multicasting purposes. The layer for implementing a function to decide whether to forward a packet to a particular Face within Multi Face or to forward to multiple Face entries simultaneously is called the Strategy layer, which is the key to efficient operation in NDN/CCN.

Processing at each NDN node on receiving an interest packet follows a three-step procedure.

1) If the requested content is found in the CS, the node delivers the content to the requestor and performs no further forwarding of that packet.
2) If an entry for the requested content already exists in the PIT, the node waits until the data packet for the same previously forwarded content request returns to that node to prevent duplicate data forwarding.
3) If no entry for that interest packet is registered in the CS or PIT, the node forwards the packet in accordance with the information in the FIB.

In addition to each NDN node having these three tables, the NDN/CCN architecture also provides for data storage in "Repository," which can store data with affixed content names. Repository connects to an NDN node through Face. In terms of content allocation, there have been discussions to the effect that it would be better for Repository to be the main storage, with the CS playing a supplementary role. If the same content were to be stored at multiple Repository locations, it would mean that multiple nodes exist as final destinations of interest packet forwarding. An implementation based on the Multi Face scheme described above could therefore be applied.

5. Trends in ICN research

We have so far described the two types of ICN architecture, but recent ICN research has been taking four main directions.

1) Optimization of cache allocation and routing

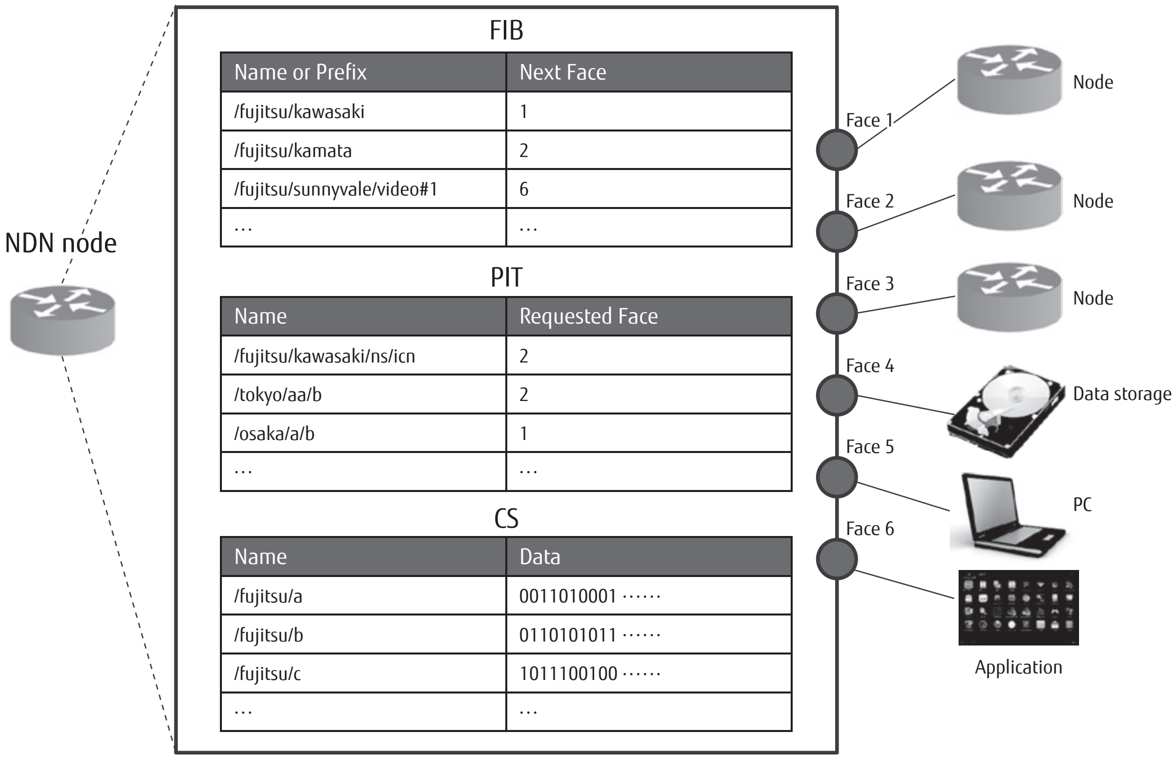


Figure 2
NDN node tables.

A great number of presentations about ICN have been made at academic conferences. There have been many reports in particular on the effect of caching, which is currently considered to be a major advantage of ICN. These reports have presented algorithms for making ICN more effective along with quantitative evaluations of their performance.[13)–15)]

2) Support of massive content (scalability)

Given that the number of items of content may be anywhere from 1 000 to 1 000 000 times the current number of Web sites on the Internet, the issue is how to provide efficient routing and a name resolution service.

3) Addition of functions not yet supported by NDN

Compared to IP, NDN has a short history, and various types of protocol for providing supplementary functions do not yet exist. Efforts are now being made to address this problem, and it is being discussed, in particular, at ICNRG, the research group mentioned above.

4) Development of platform and prototype system and search for killer applications

Studies are now underway on how to achieve a more practical NDN system, on what types of scenarios would actually amplify the advantages of NDN, and in what type of environment NDN should initially be applied in a preparatory stage prior to deployment on the scale of the Internet. In this sense, the promotion of NDN is a major undertaking.

Going forward, these four research areas will be continuously cultivated while being mutually affected. Fujitsu Laboratories of America is currently focusing on optimal cache allocation as part of item 1), as described in the next section.

6. Research at Fujitsu Laboratories of America—cache allocation problem—

One major advantage of ICN is reduced data traffic and faster response times through in-network caching. The ICN architecture itself, however, does not specify a cache algorithm—the plan is to apply specific policies to individual network operations. Optimal cache allocation is therefore of major importance, and many research results have been presented for in-network caching. This section gives an overview of the research being conducted on cache allocation at Fujitsu Laboratories of America. Details are reported elsewhere.[16] In this research, NDN/CCN is envisioned as the ICN architecture.

In NDN/CCN, the aim is to improve system efficiency by placing a much larger amount of storage within the network compared with past schemes. Large-scale placement of storage is costly, however, so a key challenge is finding the best way to use a limited amount of resources. To this end, we studied content placement for the case in which total storage capacity is fixed and the amount of storage allocated within the network minimizes download costs.

In the system model used for this study (**Figure 3**), multiple edge routers connect to a single core router, and multiple clients connect to each edge router. This model formalizes a total cost function when assuming the cost of each link and the probability of content access (content popularity). Minimizing this function determines the capacity of storage allocated to each router and the type of content placed at that router. This is a linear programming problem that can be mathematically solved using well-known techniques such as the simplex method and interior-point method.

We first searched for an optimal solution for the case in which popular content requested from clients under each edge router is the same, or, more specifically, in which the number of requests for each item of content is the same for all edge routers. The situation in which an edge router accommodates a great number of users fits this case. We found that the optimal solution for content placement was to place the most popular group of contents at edge routers and the next most popular group of contents at the core router. Since a condition in this study was that total storage capacity is fixed, the more that identical content is replicated within the system, the more that the types of cacheable content decrease. Thus, in this case, the more that the storage capacity allocated to edge routers is increased in order to place the same content at each edge router, the more that the types of content within the system decrease, which increases the cost. This is because a server must be accessed for content not cached at any node. Conversely, the number of times that content can be acquired at minimal cost between a client and edge router increases as edge-router capacity increases, which reduces the cost. The point of balance between these two factors is the optimal solution to storage placement—it is not simply a question of whether it is better to place storage only at the edge routers or at the core router.

We next looked at the case in which content popularity differs among the edge routers and searched for optimal storage allocation based on a correlation value expressing the similarity of data requests. The results of searching for optimal solutions by numerical means

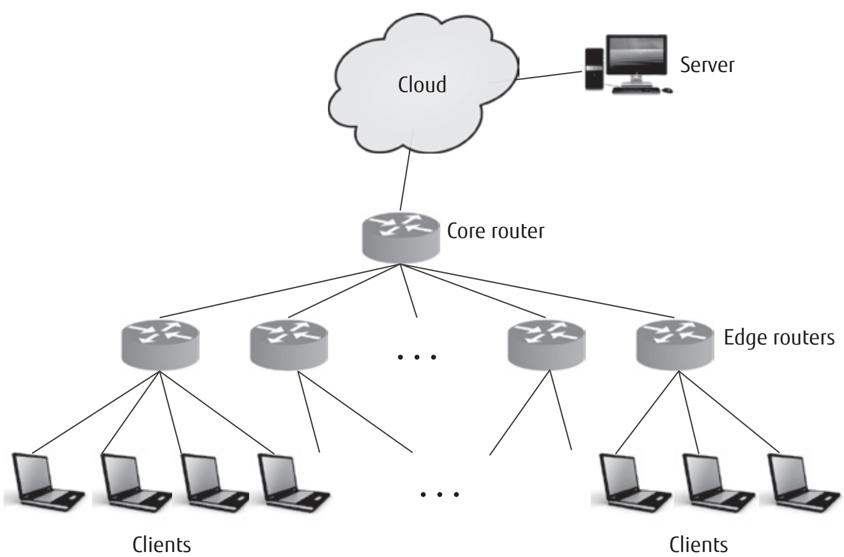


Figure 3
System model for cache allocation problem.

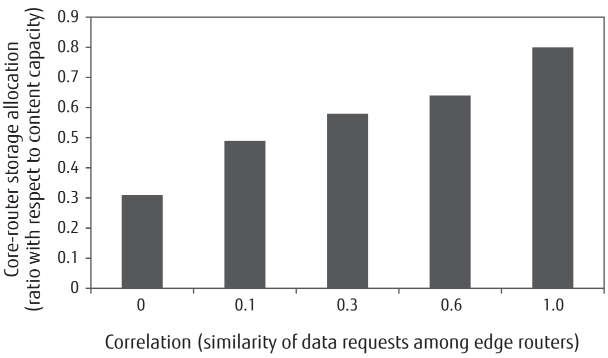
are shown in **Figure 4**. As shown, the lower the correlation, that is, the greater the disparity in popular content among edge routers, the greater the amount of storage and content that should be placed at edge routers. A low correlation means that the data requested at each edge router has low commonality with that requested at other edge routers and that the benefit of placing common data at the core router decreases. This means that increasing storage allocation at the edge routers and placing a greater variety of popular content at each edge router is effective in this case. In all cases, the solution is to place storage at all network nodes without placing a disproportionate amount at the core router or edge routers. While these findings are intuitive, actually modeling and formalizing the problem and deriving an optimal solution would be of great benefit.

We also devised two content placement methods. One is a control algorithm running on a central server that computes the popularity ranking of content and determines at which router the *n*-th popular item of content should be placed. Each router is advised of the results. The other is a control algorithm running on each router that estimates popular content in an autonomous and distributed manner on the basis of the number of requests at that router. Using an NDN simulator developed in the NDN project, we simulated and evaluated the characteristics of these algorithms along with the Leave Copy Everywhere (LCE) and Least Recently Used (LRU) strategies widely used as a cache placement/replacement algorithm. Simulation results for cache hit rate and average hop count are shown in **Figure 5**. Our algorithms achieved better results for both.

We have shown that in-network caching effectively reduces total download costs and that a superior method is to allocate storage to many nodes and to decide at which nodes to cache which content in accordance with content popularity. Our simulation results demonstrate the advantages of the NDN/CCN architecture, which features storage at network nodes and the capability of performing autonomous and dynamic caching. Our two content-placement algorithms clarify the path toward more efficient ICN network operation.

7. Conclusion

Information-centric networking is a next-generation network architecture attracting growing interest. It aims to make a transition from the existing system focused on host-to-host communications to a total service system centered about information on a global scale. This paper introduced research trends for ICN and the results of research carried out at Fujitsu Laboratories of America. Recent years have seen the establishment of many ICN-related organizations and associations, which should facilitate diverse achievements toward the further spread of ICN. ICN is still in the research stage with many problems remaining to be solved before full-scale deployment can be achieved, and we look forward to being an important part of this research and to contributing to the development and deployment of ICN.



Distribution of number of requests is same regardless of correlation value. Correlation of 1 means that number of requests for each data item is same among edge routers and correlation of 0 means that data is completely random versus number of requests.

Figure 4
Simulation results for storage allocation.

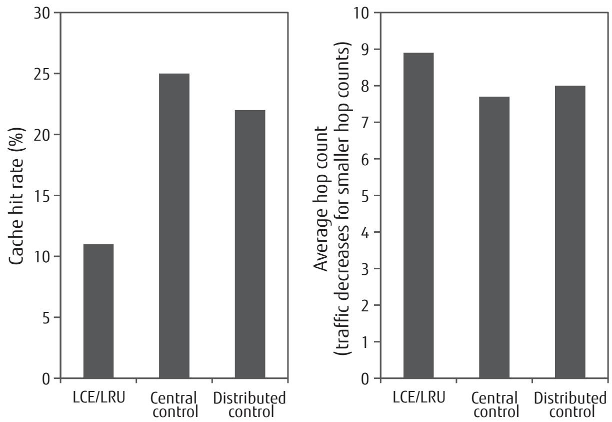


Figure 5
Simulated cache hit rate and average hop count for three cache control methods.

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