

# One Hop Lookups for Peer-to-Peer Overlays

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## Abstract

Current peer-to-peer lookup algorithms have been designed with the assumption that routing information at each member node must be kept small, so that the bookkeeping required to respond to system membership changes is also small. In this paper, we show that this assumption is unnecessary, and present a technique that maintains complete routing tables at each node. The technique is able to handle frequent membership changes and scales to large systems having more than a million nodes. The resulting peer-to-peer system is robust and can route lookup queries in just one hop, thus enabling applications that cannot tolerate the delay of multi-hop routing.

## 1 Introduction

Structured peer-to-peer overlay networks like CAN [6], Chord [10], Pastry [8], and Tapestry [11] provide a substrate for building large-scale distributed applications. These overlays allow applications to locate objects stored in the system in a limited number of overlay hops.

Peer-to-peer lookup algorithms strive to maintain a small amount of per-node routing state – typically  $O(\log N)$  – because they expect that system membership changes frequently. This expectation has been confirmed for successfully deployed systems. A recent study [9] shows that the average session time in Gnutella is only 2.9 hours. This is equivalent to saying that in a system with 100,000 nodes, there are about 19 membership change events per second.

Maintaining small tables helps keep the amount of bookkeeping required to deal with membership changes small. However, there is a price to pay for having only a small amount of routing state per node: lookups have high latency since each lookup requires contacting several nodes in sequence.

This paper questions the need to keep routing state small. We take the position that maintaining full routing state (i.e., a complete description of system membership) is viable. We present techniques that show that nodes can maintain this information accurately, yet the communication costs are low. The results imply that a peer-to-peer system can route very efficiently even though the system is large and membership is changing rapidly.

We present a novel peer-to-peer lookup system that maintains complete membership information at each node, and show analytic results that prove that the system meets our goals of reasonable accuracy and bandwidth usage. It is, of course, easy to achieve these goals for small systems. Our algorithm is designed to scale to large systems, e.g., systems with more than  $10^5$  nodes.

The rest of the paper is organized as follows: Section 2 describes the organization of our routing subsystem and Section 3 provides an analysis that shows that the overall cost of maintaining complete routing information is small. Section 4 discusses related work. We conclude with a discussion of what we have accomplished.

## 2 System Design

We consider a system of  $n$  nodes, where  $n$  is a large number like  $10^5$  or  $10^6$ . We assume dynamic membership behavior as in Gnutella, which is representative of an open Internet environment. From the study of Gnutella and Napster [9], we deduce that systems of  $10^5$  and  $10^6$  nodes would show around 20 and 200 membership changes per second, respectively. We call this rate  $r$ . We refer to membership changes as events in the rest of the paper.

Every node in the overlay is assigned a random 128-bit node identifier. Identifiers are ordered in an *identifier ring* modulo  $2^{128}$ . We assume that identifiers are generated such that the resulting set is uniformly distributed in the identifier space, for example, by setting a node's identifier to be the cryptographic hash of its network address. Every node has a predecessor and a successor in the identifier ring, and it periodically sends keep-alive messages to these nodes. Similarly, we associate a successor node with every 128-bit *key*; this is the first node in the identifier ring clockwise from *key*. This mapping from keys to nodes is based on the one used in Chord [10], but changing our system to use other mappings is straightforward.

Clients issue queries that try to reach the successor node of a particular identifier. We intend our system to satisfy a large fraction,  $f$ , of the queries correctly on the *first* attempt. Our goal is to support high values of  $f$ , e.g.,  $f = 0.99$ . A query may fail in its first attempt due to a membership change, if the notification of the change has not reached the querying node. In such a case, the query

can still be rerouted and succeed in a higher number of hops. Nevertheless, we define failed queries as those that are not answered correctly in the *first* attempt, as our objective is a one hop lookup.

To achieve this goal, every node in the system must keep a full routing table containing information about every node in the overlay. The actual value of  $f$  depends on the accuracy of this information.

## 2.1 Membership Changes

To maintain correct full routing tables, a notification of membership change events, i.e., joins and leaves, must reach every node in the system within a specified amount of time (depending on what fraction of failed queries, i.e.,  $f$ , is deemed acceptable). Our goal is to do this in a way that has reasonable bandwidth consumption (since this is likely to be the scarcest resource in the system) without increasing notification delay.

We achieve this goal by superimposing a well-defined hierarchy on the system. This hierarchy is used to form dissemination trees, which are used to propagate event information.

We impose this hierarchy on a system with dynamic membership by dividing the 128-bit circular identifier space into  $k$  equal contiguous intervals called slices. The  $i$ th slice contains all nodes currently in the overlay whose node identifiers lie in the range  $[i \cdot 2^{128}/k, (i+1) \cdot 2^{128}/k)$ . Since nodes have uniformly distributed random identifiers, these slices will have about the same number of nodes at any time. Each slice has a *slice leader*, which is chosen dynamically as the node that is the successor of the mid-point of the slice identifier space. For example, the slice leader of the  $i$ th slice is the successor node of the key  $(i + 1/2) \cdot 2^{128}/k$ . When a new node joins the system it learns about the slice leader from one of its neighbors along with other information like the data it is responsible for and its routing table.

Similarly, each slice is divided into equal-sized intervals called units. Each unit has a *unit leader*, which is dynamically chosen as the successor of the mid-point of the unit identifier space.

Figure 1 depicts how information flows in the system. Whenever a node (labeled **X** in Figure 1) detects a change in membership (its successor failed or it has a new successor), it sends an event notification message to its slice leader (1). The slice leader collects all event notifications it receives from its own slice and aggregates them for  $t_{big}$  seconds before sending a message to other slice leaders (2). To spread out bandwidth utilization, communication with different slice leaders is not synchronized, the slice leader ensures only that it communicates with each individual slice leader once every  $t_{big}$  seconds. Therefore, messages to different slice leaders are sent at different points in time and contain differ-

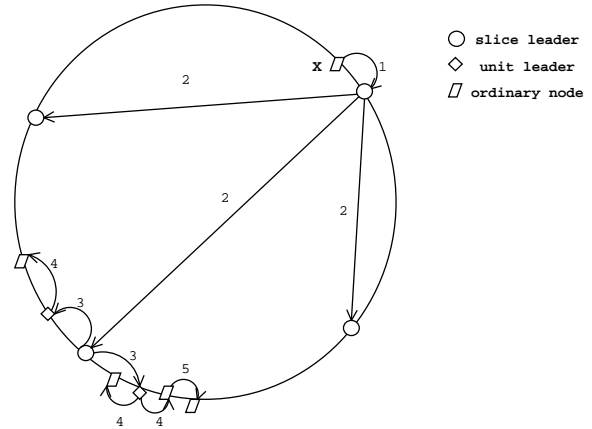


Figure 1: Flow of event notifications in the system

ent sets of events. The slice leaders aggregate messages they receive for a short time period  $t_{wait}$  and then dispatch the aggregate message to all unit leaders of their respective slices (3). A unit leader piggybacks this information on its keep-alive messages to its successor and predecessor (4). Other nodes propagate this information in one direction: if they receive information from their predecessors, they send it to their successors and vice versa. This information is piggy-backed on keep-alive messages. In this way, all nodes in the system receive notification of all events. Nodes at unit boundaries do not send information to their neighboring nodes outside their unit. This ensures that there is no redundancy in the communications: a node will get information only from its neighbor that is one step closer to its unit leader. This implies that within a unit, information is always flowing from the unit leader to the ends of the unit.

The choice of the number of levels in the hierarchy involves a tradeoff. A large number of levels implies a larger delay in propagating the information, whereas a small number of levels generates a large load at the nodes in the upper levels. We chose a three level hierarchy because it leads to reasonable bandwidth consumption, as we will show in Section 3.

We get several benefits from choosing this design. First, it imposes a structure on the system, with well-defined event dissemination trees. This structure helps us ensure that there is no redundancy in communications, which leads to efficient bandwidth usage.

Second, aggregation of several events into one message allows us to avoid small messages. Small messages represent a problem since the protocol overhead becomes significant relative to the message size, leading to higher bandwidth usage.

## 2.2 Fault Tolerance

If a query fails on its first attempt it does not return an error to an application. Instead, queries can be rerouted: if a lookup query from node  $n_1$  to node  $n_2$  fails because  $n_2$  is no longer in the system,  $n_1$  can retry the query by sending it to  $n_2$ 's successor. If the query failed because a recently joined node,  $n_3$ , is the new successor for the key that  $n_1$  is looking up, then  $n_2$  can reply with the identity of  $n_3$  (if it knows about  $n_3$ ), and  $n_1$  can contact it in a second routing step.

Since our scheme is dependent on the correct functioning of unit leaders and slice leaders, we need to recover from their failure. Note that since there are relatively few slice and unit leaders, their failures are less frequent. Therefore, we do not have to be very aggressive about replacing them in order to maintain our query success target. When a slice or unit leader fails, its successor soon detects the failure and becomes the new leader. The successor of a failed unit leader will communicate with its slice leader to obtain recent information. The successor of a failed slice leader will communicate with its unit leaders and other slice leaders to recover information about the missed events.

## 2.3 Scalability

Slice leaders have more work to do than other nodes, and this might be a problem for a poorly provisioned node with a low bandwidth connection to the Internet. To overcome this problem we can identify well connected and well provisioned nodes as "supernodes" on entry into the system. There can be a parallel ring of supernodes, and the successor (in the supernode ring) of the midpoint of the slice identifier space becomes the slice leader. We do require a sufficient number of supernodes so that we can expect that there are at least a few per slice.

As we will show in Section 3, bandwidth requirements are small enough to make most participants in the system potential supernodes in a  $10^5$  sized system (slice leaders will require 35 kbps upstream bandwidth). In a million node system we may require supernodes to be well-connected academic or corporate users (the bandwidth requirements increase to 350 kbps).

## 3 Analysis and Choice of System Parameters

This section presents an analysis of how to parameterize the system to satisfy our goal of fast propagation. To achieve our desired success rate, we will need to propagate information about events within some time period  $t_{tot}$ ; we show how to compute this quantity in Section 3.1. Yet we also require good performance, especially with respect to bandwidth utilization. Sections 3.2

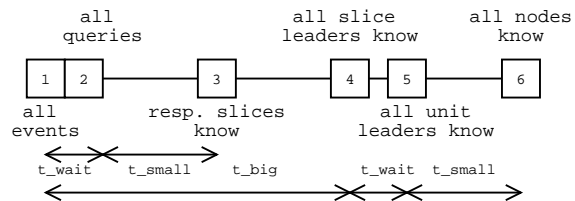


Figure 2: Timeline of the worst case situation

and 3.3 show how we satisfy this requirement by controlling the number of slices and units.

Our analysis considers only non-failure situations. It does not take into account overheads of slice and unit leader failure because these events are rare. It also ignores message loss and delay since this simplifies the presentation, and the overhead introduced by message delays and retransmissions is small compared to other time constants in the system.

Our analysis assumes that query targets are distributed uniformly throughout the ring. It is based on a worst case pattern of events, queries, and notifications: we assume all events happen just after the last slice-leader notifications, and all queries happen immediately after that, so that none of the affected routing table entries has been corrected and *all* queries targeted at those nodes (i.e., the nodes causing the events) fail. In a real deployment, queries would be interleaved with events and notifications, so fewer of them would fail.

This scenario is illustrated by the timeline in Figure 2. Here  $t_{wait}$  is the frequency with which slice leaders communicate with their unit leaders,  $t_{small}$  is the time it takes to propagate information throughout a unit, and  $t_{big}$  is the time a slice leader waits between communications to some other slice leader. Within  $t_{wait} + t_{small}$  seconds (point 3), slices in which the events occurred all have correct entries for nodes affected by the respective events. After  $t_{big}$  seconds of the events (point 4), slice leaders notify other slice leaders. Within a further  $t_{wait} + t_{small}$  seconds (point 6), all nodes in the system receive notification about all events.

Thus,  $t_{tot} = t_{detect} + t_{wait} + t_{small} + t_{big}$ . The quantity  $t_{detect}$  represents the delay between the time an event occurs and when the leader of that slice first learns about it.

### 3.1 Configuration Parameters

The following parameters characterize a system deployment:

1.  $f$  is the acceptable fraction of queries that fail in the first routing attempt
2.  $n$  is the expected number of nodes in the system

3.  $r$  is the expected rate of membership changes in the system

Given these parameters, we can compute  $t_{tot}$ . Our assumption that query targets are distributed uniformly around the ring implies that the fraction of failed queries is proportional to the expected number of incorrect entries in a querying node's routing table. Given our worst case assumption, all the entries concerning events that occurred in the last  $t_{tot}$  seconds are incorrect and therefore the fraction of failed queries is  $\frac{r \times t_{tot}}{n}$ . Therefore, to ensure that no more than a fraction  $f$  of queries fail we need:

$$t_{tot} \leq \frac{f \times n}{r}$$

For a system with  $10^6$  nodes, with a rate of 200 events/s, and  $f = 1\%$ , we get a time interval as large as 50s to propagate all information. Note also that if  $r$  is linearly proportional to  $n$ , then  $t_{tot}$  is independent of  $n$ . It is only a function of the desired success rate.

### 3.2 Slices and Units

Our system performance depends on the number of slices and units:

1.  $k$  is the number of slices the ring is divided into.
2.  $u$  is the number of units in a slice.

Parameters  $k$  and  $u$  determine the expected unit size. This in turn determines  $t_{small}$ , the time it takes for information to propagate from a unit leader to all members of a unit, given an assumption about  $h$ , the frequency of keep-alive probes. From  $t_{small}$  we can determine  $t_{big}$  from our calculated value for  $t_{tot}$ , given choices of values for  $t_{wait}$  and  $t_{detect}$ . (Recall that  $t_{tot} = t_{detect} + t_{big} + t_{wait} + t_{small}$ .)

To simplify the analysis we will choose values for  $h$ ,  $t_{detect}$ , and  $t_{wait}$ . As a result our analysis will be concerned with just two independent variables,  $k$  and  $u$ , given a particular choice of values for  $n$ ,  $r$ , and  $f$ . We will use one second for both  $h$  and  $t_{wait}$ . This is a reasonable decision since the amount of data being sent in probes and messages to unit leaders is large enough to make the overhead in these messages small (e.g., information about 20 events will be sent in a system with  $10^5$  nodes). Note that with this choice of  $h$ ,  $t_{small}$  will be half the unit size. We will use three seconds for  $t_{detect}$  to account for the delay in detecting a missed keep-alive message and a few probes to confirm the event.

### 3.3 Cost Analysis

Our goal is to choose values for  $k$  and  $u$  in a way that reduces bandwidth utilization. In particular we are concerned with minimizing bandwidth use at the slice leaders, since they have the most work to do in our approach.

Bandwidth is consumed both to propagate the actual data, and because of the message overhead.  $m$  bytes will be required to describe an event, and the overhead per message will be  $v$ .

There are four types of communication in our system.

1. *Keep-alive messages:* Keep-alive messages form the base level communication between a node and its predecessor and successor. These messages include information about recent events. As described in Section 2, our system avoids sending redundant information in these messages by controlling the direction of information flow (from unit leader to unit members) and by not sending information across unit boundaries.

Since keep-alive messages are sent every second, every node that is not on the edge of a unit will send and acknowledge an aggregate message containing, on average,  $r$  events. The size of this message is therefore  $r \cdot m + v$  and the size of the acknowledgement is  $v$ .

2. *Event notification to slice leaders:* Whenever a node detects an event, it sends a notification to its slice leader. The expected number of events per second in a slice is  $\frac{r}{k}$ . The downstream bandwidth utilization on slice leaders is therefore  $\frac{r \cdot (m+v)}{k}$ . Since each message must be acknowledged, the upstream utilization is  $\frac{r \cdot v}{k}$ .

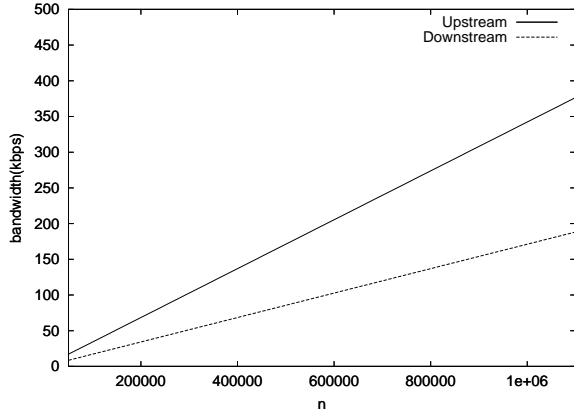
3. *Messages exchanged between slice leaders:* Each message sent from one slice leader to another batches together events that occurred in the last  $t_{big}$  seconds in the slice. The typical message size is, therefore,  $\frac{r}{k} \cdot t_{big} \cdot m + v$  bytes. During any  $t_{big}$  period, a slice leader sends this message to all other slice leaders ( $k - 1$  of them), and receives an acknowledgement from each of them. Since each slice leader receives as much as it gets on average, the upstream and downstream use of bandwidth is symmetric. Therefore, the bandwidth utilization (both upstream and downstream) is

$$\left( \frac{r \cdot m}{k} + \frac{2 \cdot v}{t_{big}} \right) \cdot (k - 1)$$

4. *Messages from slice leaders to unit leaders:* Messages received by a slice leader are batched for one second and then forwarded to unit leaders. In one second,  $r$  events happen and therefore the aggregate message size is  $(r \cdot m + v)$  and the bandwidth utilization is

$$(r \cdot m + v) \cdot u$$

Table 1 summarizes the net bandwidth use on each node. To clarify the presentation, we have removed insignificant terms from the expressions.



**Figure 3:** Bandwidth use on a slice leader with  $r \propto n$

	Upstream	Downstream
Slice Leader	$r \cdot m \cdot (u + 2) + \frac{2 \cdot v \cdot k}{t_{big}}$	$r \cdot m + \frac{2 \cdot v \cdot k}{t_{big}}$
Unit Leader	$2 \cdot r \cdot m + 3 \cdot v$	$r \cdot m + 2 \cdot v$
Other nodes	$r \cdot m + 2 \cdot v$	$r \cdot m + 2 \cdot v$

**Table 1:** Summary of bandwidth use

Using these formulas we can compute the load on non-slice leaders in a particular configuration. In this computation we use  $m = 20$  bytes and  $v = 40$  bytes. In a system with  $10^5$  nodes, we see that the load on an ordinary node is 3.84 kbps and the load on a unit leader is 7.36 kbps upstream and 3.84 kbps downstream. For a system with  $10^6$  nodes, these numbers become 38.4 kbps, 73.6 kbps, and 38.4 kbps respectively.

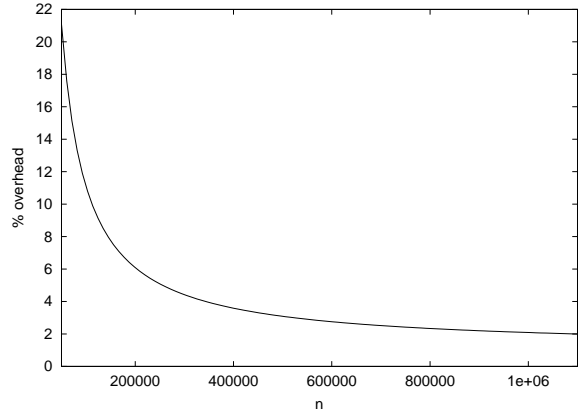
From the table it is clear that the upstream bandwidth required for a slice leader is likely to be the dominating and limiting term. Therefore, we shall choose parameters that minimize this bandwidth. By simplifying the expression and using the interrelationship between  $u$  and  $t_{big}$  (explained in Section 3.2) we get a function that depends on two independent variables  $k$  and  $u$ . By analyzing the function, we deduce that the minimum is achieved for the following values:

$$k = \sqrt{\frac{r \cdot m \cdot n}{4 \cdot v}}$$

$$u = \sqrt{\frac{4 \cdot v \cdot n}{r \cdot m \cdot (t_{tot} - t_{wait} - t_{detect})^2}}$$

These formulas allow us to compute values for  $k$  and  $u$ . For example in a system of  $10^5$  nodes we want roughly 500 slices each containing 5 units. In a system of  $10^6$  nodes, we still have 5 units per slice, but now there are 5000 slices.

Given values for  $k$  and  $u$  we can compute the unit size



**Figure 4:** Aggregate bandwidth overhead of the scheme as a percentage of the theoretical optimum

and this in turn allows us to compute  $t_{small}$  and  $t_{big}$ . We find that we use least bandwidth when

$$t_{small} = t_{big}$$

Thus, we choose 23 seconds for  $t_{big}$  and 23 seconds for  $t_{small}$ .

Given these values and the formulas given in Table 1, we can plot the bandwidth usage per slice leader in systems of various sizes. The results of this calculation are shown in Figure 3. Note that the load increases only linearly with the size of the system. The load is quite modest in a system with  $10^5$  nodes (35 kbps upstream bandwidth), and therefore even nodes behind cable modems can act as slice leaders in such a system. In a system with  $10^6$  nodes the upstream bandwidth required at a slice leader is approximately 350 kbps. Here it would be more appropriate to limit slice leaders to being machines on reasonably provisioned local area networks. For larger networks, the bandwidth increases to a point where a slice leader would need to be a well-provisioned node.

Figure 4 shows the percentage overhead of this scheme in terms of aggregate bandwidth used in the system with respect to the hypothetical optimum scheme with zero overhead. In such a scheme, the cost is just the total bandwidth used in sending  $r$  events to every node in the system every second, i.e.,  $r \cdot n \cdot m$ . Note that the overhead in our system comes from the per-message protocol overhead. The scheme itself does not propagate any redundant information. We note that the overhead is approximately 20% for a  $10^5$  sized system and goes down to 2% for  $10^6$  sized system. This result is reasonable because messages get larger and the overhead becomes less significant as system size increases.

## 4 Related Work

Rodrigues et al. [7] proposed a single hop distributed hash table but they assumed a much smaller peer dynamics, like that in a corporate environment, and therefore did not have to deal with the difficulties of rapidly handling a large number of membership changes with efficient bandwidth usage. Douceur et al. [2] present a system that routes in a constant number of hops, but that design assumes smaller peer dynamics and searches can be lossy.

Kelips [3] uses  $\sqrt{n}$  sized tables per node and a gossip mechanism to propagate event notifications to provide constant time lookups. Their lookups, however, are constant time only when the routing table entries are reasonably accurate. As seen before, these systems are highly dynamic and the accuracy of the tables depends on how long it takes for the system to converge after an event. The expected convergence time for an event in Kelips is  $O(\sqrt{n} \times \log^3(n))$ . While this will be tens of seconds for small systems of around a 1000 nodes, for systems having  $10^5$  to  $10^6$  nodes, it takes over an hour for an event to be propagated through the system. At this rate, a large fraction of the routing entries in each table are likely to be stale, and a correspondingly large fraction of queries would fail on their first attempt.

Mahajan et al. [5] also derive analytic models for the cost of maintaining reliability in the Pastry [8] peer-to-peer routing algorithm in a dynamic setting. This work differs substantially from ours in that the nature of the routing algorithms is quite different – Pastry uses only  $O(\log N)$  state but requires  $O(\log N)$  hops per lookup – and they focus their work on techniques to reduce their (already low) maintenance cost.

Liben-Nowell et al. [4] provide a lower-bound on the cost of maintaining routing information in peer-to-peer networks that try to maintain topological structure. We are designing a system that requires significantly larger bandwidth than in the lower bound because we aim to achieve a much lower lookup latency.

## 5 Conclusion

This paper shows that maintaining only a small amount of routing state at each node is not necessary in a dynamic peer-to-peer system. We present a design for a system that maintains complete membership information with reasonable bandwidth requirements.

Currently deployed and proposed systems vary greatly in size and membership behavior. Corporate and academic environments have far fewer configuration events; e.g., half of 64, 610 machines probed in a software company are up over 95% of the time [1]. If we design our system to deal with these relatively stable environments, we will have much lower bandwidth requirements.

For systems of size much greater than a million nodes, routing tables become large and it may not be desirable to keep them completely in primary memory. In such a deployment scenario, we may want to use a two-hop routing scheme instead: The querying node contacts a node in the slice containing the target node. That node then redirects the query to the target node. In such a scheme, the querying node needs to be aware of only a few nodes of other slices, leading to smaller routing tables. It is not difficult to adapt our approach to such a scheme, with large savings in bandwidth because very little inter-slice information needs to be propagated.

Currently peer-to-peer storage systems have high lookup latency and are therefore only well-suited for applications that do not mind high-latency store and retrieve operations (e.g., backups) or that store and retrieve massive amounts of data (e.g., a source tree distribution). Moving to more efficient routing removes this constraint. This way we can enable a much larger class of applications for peer-to-peer systems.

## Acknowledgements

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