Modeling the economics of Loc/ID Split for the Future Internet

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Abstract. The network research community is actively working on the design of the Future Internet, aiming at solving scalability issues that the current Internet is facing. It is widely recognized that the Locator/ID Split paradigm fits well the requirements for the new, more scalable, Future Internet architecture. Both the academy and the industry have already produced several technical proposals, with their own peculiarities and merits. However, despite such an effort, it is still unclear, how the Locator/ID Split will be deployed, what are the drivers of its adoption, who will adopt it, and how the adoption process will most likely evolve in time. In this paper, we answer to these questions by presenting an adoption model for the Locator/ID Split paradigm.

Keywords. Locator/ID Split, Future Internet, Routing, Adoption Model.

Introduction

Nowadays, there is a growing concern on scalability issues the current Internet is facing ([1], [2]), with the most pressing issue being the super linear growth of the BGP routing table [3]. This does not mean that the Internet is approaching a hard scalability limit that, once reached, will cause it to collapse. Rather, the key point is that the whole Internet is evolving toward such a complex system that the Operational Expenses (OpEx) cannot be sustained anymore.

Almost three years ago, the Routing Research Group (RRG [4]) of the IRTF (Internet Research Task Force) was expressly re-chartered to design a new and cheaper Future Internet architecture. So far the main outcome has been the recognition that splitting the IP addressing space into an end-system addressing space (the identifiers - IDs) and a routing addressing space (the locators - Loc) will solve or at least alleviate a large part of the issues [5]. The technical implication of such architecture, which is currently referred as Loc/ID Split paradigm, is the need to maintain mappings between IDs and Locators [6]. These mappings are distributed through a Mapping Distribution System (MDS) (e.g., [7]), and then stored in a local cache for the ongoing communications. Additionally, tunneling or address translation operations are needed, since IDs are not injected anymore in the BGP routing infrastructure (hence the improved scalability).

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Although the idea of improving the Internet architecture with some form of separation of the identity and the location dates back to the mid-90s ([8], [9], [10]), it has gained wide support only lately due to the apparent explosion of the OpEx. Indeed, the success of Loc/ID Split technology depends not only on its technical merits, but also on the economical aspects of its deployment. In this paper we shed light on this last point by creating an economic model of the adoption process of the Loc/ID Split paradigm without focusing on any specific technical proposal. Our aim is to understand how the cost evolution influences the adoption process, who will adopt such a technology, and what are their reasons for adoption. We start with a high level analysis of the stakeholders in Section 1. Then, we introduce the cost model in Section 2 and use it in Section 3 to analyze the cost evolution and its impact on adoption process. Finally, we conclude our findings in Section 4.

1. Stakeholder analysis

Loc/ID Split is a general paradigm that can be applied in several different places of the Internet, depending on where the split is actually done. For instance, Loc/ID Split can be done on end-host systems, like in the case of Shim6 [11] and HIP [12], introducing benefits mostly related to multi-homing support and resiliency to location change. Alternatively, Loc/ID Split can be done on domain border routers, like in LISP [13], directly targeting the reduction of the prefix entries in the BGP routing table. Other benefits are introduced in both cases, e.g., improved traffic engineering and reduced provider lock-in. Regardless of their importance, they are not the main objective.

In this paper, we focus on the deployment of Loc/ID Split on border routers (i.e., à la LISP). We believe that the main economic driver for the deployment of such technology will be the reduction of OpEx, obtained reducing the number of prefix entries that need to be managed, stored, and propagated to maintain full connectivity. To this end, it is important to identify the existing stakeholders interested in deploying Loc/ID Split. In such a context, Network Domains (NDs) are the main stakeholders, since they target at reducing their OpEx by reducing the size of the BGP routing table. Nevertheless, NDs have different costs and benefits in adopting Loc/ID Split, depending on where they are positioned in the Internet:

**Stub NDs** are leafs of the Internet topology, being only source/destination of traffic, without providing transit connectivity. Their benefits mainly consist in avoiding provider lock-in, gaining more control on the inbound traffic, and reducing the size of the routing table (since their prefixes will not be injected anymore in the BGP infrastructure). The main costs are related to the physical deployment of the Loc/ID Split technology on their border routers, which also include interoperability solutions to guarantee connectivity with legacy NDs (i.e., NDs not using Loc/ID Split).

**Core NDs** are rather at the centre of the Internet topology, providing the core connectivity infrastructure. Reduced routing table size is also Core NDs’ key benefit but it is dependent on the Stub NDs adoption of Loc/ID Split. Further, since Stub NDs are the ones generating most of the churn, an additional gain is the reduction

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2 Due to space constrains, we omit the analysis of possible new stakeholders (e.g., mapping service providers), which in turn can generate new business models.
of such a churn. There are no direct costs for Core NDs, unless they are willing to deploy Loc/ID Split to further increase the welfare of the Internet. The difference of benefits between Stub and Core NDs plays a key role on who will start deploying Loc/ID Split. As we will show in the remainder of the paper, cost reduction can be small for early adopters. In this case Stub NDs have stronger incentives, since, even if cost reduction is small, by adopting Loc/ID Split they avoid provider lock-in and have full control of inbound traffic. Core NDs benefit from Stub NDs adopting Loc/ID Split, since their own BGP tables will shrink as well. However, as we will show in Section 3, with well engineered solutions the cost reduction will become important as long as NDs adopt Loc/ID Split, hence strengthening the incentives for Core NDs to deploy the Loc/ID Split technology.

2. Cost model of Loc/ID Split adoption

As mentioned earlier, we believe that the main driver for adopting Loc/ID Split is the reduction of the information (entries) that NDs have to deal with in order to maintain end-to-end connectivity. In the context of Loc/ID Split, the generic term “entry” does not refer only to the entries in the BGP RIB, but also the entries in the local cache, as well as the entries maintained locally in the Mapping Distribution System. Figure 1 shows a snapshot of today’s situation with large BGP RIB (left), and what will be the situation once the Loc/ID Split adoption process has completed (right).

Each type of entry represents an operational cost as well as a capital cost in terms of resources (e.g., memory). Regardless the specific relationship with the monetary cost and neglecting the switching cost, it is appropriate and sufficiently general to adopt the number of entries as the cost metric when modeling the adoption of Loc/ID Split. More specifically we model the number of entries per ND needed for the full connectivity. Currently each ND has to store one entry per each other ND (cost = 1), but thanks to Loc/ID split it is possible to reduce the number of entries per Network Domain (cost < 1).

Following an approach similar to the one proposed by Joseph et al. [15], Equation (1) formulates the total cost $C_T$ for a generic ND as the average number of entries stored per-ND:

$$ C_T = X_L C_{(L \rightarrow B)}(X_L) + (1 - X_L) C_{(B \rightarrow L)}(X_L). $$

(1)

Where $C_{(L \rightarrow B)}(X_L)$ and $C_{(B \rightarrow L)}(X_L)$, which are detailed in the next sections, have the following meaning:

$C_{(L \rightarrow B)}(X_L)$ is the cost (i.e., the number of entries stored per-ND) for a domain that has adopted Loc/ID Split, including the cost to assure connectivity to legacy BGP NDs.

$C_{(B \rightarrow L)}(X_L)$ is the cost (i.e., the number of entries stored per-ND) for a legacy domain that has not adopted Loc/ID Split, including the cost to assure connectivity toward Loc/ID Split enabled NDs.
2.1. Cost for Loc/ID Split NDs

The cost $C_{(L\rightarrow B)}(X_L)$ can be modeled as the sum of four terms: 1) the cost of the cache, 2) the cost of the connectivity infrastructure, 3) the cost to reach legacy BGP NDs, and 4) the cost of the Mapping Distribution System (MDS).

**The cost of maintaining a cache of mappings** can be simply formalized as $\alpha X_L$. The parameter $\alpha$ (ranging from 0 to 1) represents the percentage of Loc/ID Split enabled NDs that are in average present in the cache. Otherwise stated, $\alpha X_L$ expresses the average size of the mapping's cache in terms of entries for the ongoing communication. Even if this quantity is traffic driven, it is possible to have an average estimation of the size of Loc/ID Split cache, by means of traffic analysis. An example of such estimation can be found in the work of Iannone et al. [6].

**The connectivity infrastructure cost** is proportional to the number of Core NDs that have adopted Loc/ID Split and can be formalized as $\gamma X_L C_I$. $C_I$ represents the percentage of prefixes that have to be maintained in order to guarantee the connectivity existing in the Default Free Zone (DFZ). In other words, this can be seen as the size of the Locator addressing space. $C_I$ can be easily evaluated by counting the number of Core ND prefixes in the BGP routing table. $\gamma$ (ranging between 1 and 0) is an aggregation factor expressing the fact that once Stub NDs have switched to Loc/ID Split, a large part of de-aggregation present in today's Internet can be avoided, which reduces the infrastructure connectivity cost.

**The cost to reach legacy BGP NDs** is simply given as the percentage of networks domains that have not yet adopted Loc/ID Split $(1 - X_L)$ and thus need to be present in the BGP's RIB.

**The cost of the Mapping Distribution System** is proportional to the number of entries that it has to manage in order to guarantee connectivity among Loc/ID split NDs and can be formalized as $\omega X_L$. The parameter $\omega$ (ranging from 0 to 1) expresses what percentage of the mappings present in the MDS needs to be stored locally. Note that this term is present only in the case that the network domain is part of the Mapping Distribution System otherwise the cost is zero.

Putting together all of the abovementioned costs leads to the following formalization of the cost for a Loc/ID Split ND in Equation (2):

$$C_{(L\rightarrow B)}(X_L) = \alpha X_L + (1 - X_L) + \gamma X_L C_I + \omega X_L.$$

2.2. Cost for legacy BGP NDs

The cost $C_{(B\rightarrow L)}(X_L)$ for a legacy ND that has not adopted Loc/ID Split can be modeled as the sum of two terms: 1) the cost to reach other legacy BGP NDs and 2) the cost to reach Loc/ID adopters.

**The cost to reach other legacy BGP NDs** is simply given as the percentage $(1 - X_L)$ of NDs that have not adopted Loc/ID Split.

**The cost to reach Loc/ID Split enabled sites** can be formalized as $\beta X_L$, where $\beta$ (ranging from 0 to 1) represents an aggregation factor. To make Loc/ID Split adopters reachable from legacy BGP NDs, a proxy-based solution, like for instance [14], can be

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3 This should not be confused with the mapping cache. The cache temporarily stores mappings that are needed for the ongoing communications, while the mapping distribution system is basically a distributed database of all available mappings.
Table 1. Summary of the parameters introduced in the adoption model.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{(B \rightarrow L)}$</td>
<td>Cost (i.e., the number of entries stored per-ND) for a Loc/ID Split adopter ND</td>
<td>[0 – ∞]</td>
</tr>
<tr>
<td>$C_{(B \rightarrow L)}$</td>
<td>Cost (i.e., the number of entries stored per-ND) for a legacy BGP ND</td>
<td>[0 – ∞]</td>
</tr>
<tr>
<td>$C_T$</td>
<td>Total cost for a generic ND (i.e., the average number of entries stored per-ND)</td>
<td>(0 – ∞)</td>
</tr>
<tr>
<td>$X_L$</td>
<td>% of NDs that are in Loc/ID Split enabled ND</td>
<td>[0 – 1]</td>
</tr>
<tr>
<td>$C_I$</td>
<td>% of NDs necessary to maintain the Connectivity Infrastructure</td>
<td>(0 – 1)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Cache Aggregation Factor</td>
<td>(0 – 1)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Legacy ND Proxy Aggregation Factor</td>
<td>(0 – 1)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Connectivity Infrastructure Aggregation Factor</td>
<td>(0 – 1)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Mapping Distribution System Load Factor</td>
<td>(0 – 1)</td>
</tr>
</tbody>
</table>

used. This injects large aggregates of the ID space in the BGP routing infrastructure. The factor $\beta$ expresses such a degree of aggregation.

By adding up the two abovementioned costs we formalize the cost for a legacy ND in Equation (3):

$$C_{(B \rightarrow L)}(X_L) = \beta X_L + (1 - X_L).$$

(3)

2.3. Total cost

By substituting Equations (2) and (3) in Equation (1), it is possible to derive the total cost $C_T$ in Equation (4):

$$C_T(X_L) = X_L \left[ \alpha \omega X_L + (1 - X_L) + \gamma X_L C_I + \omega X_L \right] + (1 - X_L) \left[ \beta X_L + (1 - X_L) \right].$$

(4)

The different parameters and quantities of the equation, which have been introduced throughout the whole section, are summarized in Table 1.

3. Cost evolution analysis

In this section we use the proposed model to analyze the cost evolution during the adoption process of Loc/ID Split. We first look at the cost evolution for single NDs, namely $C_{(B \rightarrow L)}$ and $C_{(B \rightarrow L),}$ then at the total cost $C_T$ evolution. Finally we draw some conclusions concerning the adoption of Loc/ID Split where we assume that NDs make their adoption choice based on the global welfare (i.e., minimized global costs).

3.1. Single Loc/ID Split ND

The cost in terms of entries for a Loc/ID split ND has been formalized in Equation (2). In order to analyze evolution of this cost we have to define suitable values for the cache cost, interconnectivity cost and MDS cost.

**Cache cost:** Extensive measurements performed by Iannone et al. [6] show how a cache can be engineered by tuning the cache timeout, in order to reduce its size with only a small decrease in the hit ratio. In particular, it is possible to have a cache as small as 3.3% of the BGP prefix space, while maintaining a hit ratio as high as 94%.
This means that a realistic value of $\alpha$ is around 3.3% of the percentage $X_L$ of NDs that have adopted Loc/ID Split: $\alpha = 0.033 \cdot X_L$.

**Interconnectivity cost:** Adopting Loc/ID Split does not mean that the BGP routing infrastructure in the Default Free Zone (DFZ) will disappear, but rather that the BGP tables will shrink to smaller size. The smaller BGP tables are represented in our model by the factor $\gamma C_i$. Simulation study of Quoitin et al. [5] showed that by withdrawing the prefixes of stub networks from the DFZ it is possible to have a higher degree of aggregation and reduce the size of BGP tables up to a factor of 10. This means that a good estimation of $\gamma$ is 10%. Nevertheless, it is unlikely that the aggregation is high from the beginning. Hence $\gamma$ can be modeled in a way that it lowers to 10% as more NDs adopt Loc/ID Split: $\gamma = 0.10 + 0.9(1-X_L)$. The other factor to take into account is $C_i$. In the current Internet, 60% of the prefixes are announced by transit network domains: $C_i = 0.6$.

**Mapping Distribution System cost:** The parameter $\omega$ expresses the local cost imposed by the mapping distribution system. The smaller the factor, the lower is the cost, since it means that fewer mappings need to be maintained locally. Note, however, that the whole MDS stores always all of the existing mappings. A network domain can even decide to outsource the MDS functionality. This means that it will not directly participate in the MDS infrastructure, but it rather relies on the possibility to just query the MDS which is maintained by other network domains or by a third party. In the case of outsourcing the cost is obviously 0, since the network domain does not need to maintain any entry for the mapping distribution service.4

In the case of the NDs participating in the MDS infrastructure the cost depends on the architecture used to implement the distributed mapping database. It is possible to identify three different main architecture types:

**Flat Pull:** Flat Pull architecture consists of a distributed infrastructure without hierarchical organization; the requested information can be pulled through a simple query. Main examples of this type of architecture are DHT-based lookup infrastructures [7]. The average number of entries (in percentage) in such a structure is given by the number of nodes present in the infrastructure divided by the total number of prefixes in the ID space. The best case is when every ND has only one node in the infrastructure. Taking today's number of entries in the BGP table (~300,000), this is equivalent to having a cost of around 0.0003% per network domain.

**Hierarchical Pull:** Contrary to the previous case, this one is a distributed infrastructure with a hierarchical organization. The needed information can be pulled through a query that can recursively propagate through the hierarchy. This kind of infrastructure is very similar to the DNS system. The average number of entries per-domain (in percentage) in such a structure is given by the average proportion of entries of Flat Pull architecture (the lowest level of the hierarchy) multiplied by the logarithm of number of levels in the hierarchy. Assuming the best case of the flat pull and a balanced binary tree, the load is 5 times greater than in the Flat Pull case.

**Push:** This kind of architecture has the opposite approach compared to the previous two. Instead of pulling the information from the infrastructure when needed, the infrastructure pushes the information to all nodes that are part of the system. This means that every node has global knowledge of all available mappings and no cache is needed anymore. In this particular case $\omega = 1$ while $\alpha = 0$.

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4 Note that this does not count for the monetary cost of the service from a third party.
The cost evolution for all of the three mapping architectures is depicted in Figure 2, where the cost axis is in log scale because the costs of Flat Pull and Hierarchical Pull are very close to each other and decrease very fast with the increasing proportion $X_L$ of adopters. This is due to the fact that when the number of adopters increases, the cost per-single ND becomes very small since the cost is evenly distributed between all adopters. On the contrary, in the Push model the cost is always increasing and proportional to the number of adopters.

Figure 3 finally shows the entire cost for Loc/ID Split adopters. As can be observed, the mapping cost in the case of the Pull model is very small and has almost no impact. On the contrary, in the case of Push model the cost rises until reaching its maximum in the middle of the adoption process, and then lowers. The decrease of the cost is not due to reduction of the mapping cost, since in reality it increases linearly with the number of adopters. Rather, the reduction is due to the fact that the connectivity infrastructure will allow aggregating prefixes as long as the number of adopters increases. In other words, the decreasing $\gamma$ allows overall cost reduction.

### 3.2. Single Legacy BGP ND

The cost in terms of entries for a legacy BGP NDs has been formalized in Equation (3). Figure 4 presents the cost evolution for a legacy ND as the function of $X_L$. This cost decreases with a slope that depends on the factor $\beta$.

Let us first analyze the case where aggregation factor $\beta$ is constant throughout the adoption process (dashed lines in Figure 4). On one hand, in the case $\beta = 1$, there is no cost reduction at all. This is due to the fact that prefixes that are withdrawn from legacy ND’s BGP RIB are now announced unchanged by the proxy solution. From this we can observe that any interconnectivity solution based on a proxy approach provides benefits only in the case that prefixes of Loc/ID Split NDs are massively aggregated.

On the other hand, the case $\beta = 0$ shows the steepest decrease in the cost. However, $\beta = 0$ cannot be considered, since it means that no prefixes are announced to reach Loc/ID Split NDs from legacy BGP NDs. This would result in no interconnectivity, which makes this case unacceptable.

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5 For simplicity we just plot the Flat Pull cost, since the Hierarchical Pull model is pretty close.
Assuming constant $\beta$ is clearly an unrealistic hypothesis. A more realistic assumption is to consider a linear decrease of $\beta$ for increasing values of $X_L$. In this case, the cost reduces slowly when the number of adopters is small, but the pace accelerates when the number of adopters increases. This matches with the probable evolution of the adoption. At the beginning the prefixes of few adopters are not easily aggregatable by the proxy solution but the chances for aggregation increase along with the increasing number of adopters.

3.3. Total Cost Analysis

The total cost $C_T$ for a generic ND as the average number of entries stored per-ND is formalized in Equation (4). With some trivial mathematical transformations, this equation can be re-written in the form:

$$C_T(X_L) = (\alpha + \gamma C_I + \omega - \beta)X_L^2 + (\beta - 1)X_L + 1. \tag{5}$$

Equation (5) is used in Figure 5 to draw the evolution of the total cost as a function of the number of NDs that adopt Loc/ID Split. The figure neglects the mapping cost (i.e., $\omega = 0$), keeps $(\alpha + \gamma C_I)$ constant and shows the cost evolution for several constant values of $\beta$ as well as for a linearly decreasing value of $\beta$ (i.e., increasing aggregation).

If no ND adopts Loc/ID Split, the cost is equal to $C_T(X_L = 0) = 1$. Since all the quantities are expressed in a relative form this translates in having 100% of the actual cost (i.e., the cost of current BGP RIB). Otherwise, if all the NDs adopt the technology, the total cost becomes $C_T(X_L = 1) = (\alpha + \gamma C_I)$. On one hand, this shows the correctness of the model, since once every ND has adopted the technology the cost does not depend on the interoperability technology (i.e., the $\beta$ factor). On the other hand, it correctly shows that the final cost depends only on the size of cache ($\alpha$) and the connectivity infrastructure ($\gamma C_I$).

In the same plot, it can be observed that the cost reduction is slow at the beginning, but accelerates for increasing number of adopters. Nevertheless, this is not always true. As shown in Figure 6, if the final cost is small, the curve has a steep slope, thus making even late adopters to decrease the cost. However, if the final cost is high, the trend of the slope can even be inverted, making the late adopters increase the cost. This last point leads to the conclusion that if Loc/ID Split does not provide sufficient reduction in the cost, i.e., high benefits, the adoption process of the technology will never complete, because late adopters thinking about global welfare have no sufficient incentives for adoption (they may even have deterrence since the cost increases).
Table 2. Total cost for different mapping models.

<table>
<thead>
<tr>
<th>Distribution Model</th>
<th>Cache</th>
<th>Mapping</th>
<th>Interconnectivity</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Pull</td>
<td>3.3%</td>
<td>0.0033%</td>
<td>6%</td>
<td>9.3%</td>
</tr>
<tr>
<td>Hierarchical Pull</td>
<td>3.3%</td>
<td>0.0165%</td>
<td>6%</td>
<td>9.3165%</td>
</tr>
<tr>
<td>Push</td>
<td>0</td>
<td>100%</td>
<td>6%</td>
<td>106%</td>
</tr>
</tbody>
</table>

Finally, in Figure 7 we present the evolution of total cost including the mapping cost (both pull and push model). As can be observed, the Pull model (flat or hierarchical) introduces some costs, i.e., some entries that need to be managed, but it does not represent the major part of the overall cost.

From a static perspective the cost of the MDS is not high. However, it has to be noted that the current analysis does not take into account the dynamics of the system, meaning that it does not model the load in terms of queries that the system has to support. Nevertheless, the load of the MDS is similar to the current load of the DNS system [6], and thus it is not a critical issue.

The use of Push model leads to increased total cost in the end of the adoption process. However, it is interesting to note that this is not the case all the time. During the adoption process the overall cost can be reduced, even if the reduction is slower than in the Pull case. This is not because of the mapping system itself, but rather due to the fact that the interconnectivity infrastructure can be strongly aggregated (i.e., the term $\gamma C_I$ can be very small), which reduces the overall cost. Nonetheless, using a Push model will basically lead to a world where the adoption process will never complete since late adopters will increase the overall cost of the Internet. This is better shown in Table 2, which summarizes the final total cost for the different mapping distribution system architectures when all of the NDs have adopted Loc/ID Split.

4. Conclusion

The Loc/ID Split cost model and analysis proposed in this paper is a useful tool in deriving the relation between important architectural parameters, incentives, and the possible deployment scenarios. In summary, Loc/ID Split adoption depends on -how much- the cost can be reduced and -how efficient- deployed components are.

In particular, the proposed analysis shows that to have a cost reduction, and hence incentives to adopt Loc/ID Split, the sum of the cost of the cache ($\alpha$), the connectivity infrastructure ($\gamma C_I$), and the mapping distribution system ($\omega$) must be lower than the
original cost of today's BGP Internet. The adoption process will offer more incentives if the interoperability technology (β) greatly reduces the number of prefixes through aggregation. Nevertheless, if the interoperability technology performs too well, late adopters can actually increase the overall cost, which may prevent complete adoption.

The current assumption that NDs would base their adoption decision on the global cost minimization is naive in the commercial Internet. Thus in the further work we will analyze the adoption incentives assuming selfish NDs that try to minimize only their own costs. This analysis will also take into account the switching costs and possible obstructions for deployment, which can have major impact on the adoption decision.

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