Novel Genes from Formation to Function

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The study of the evolution of novel genes generally focuses on the formation of new coding sequences. However, equally important in the evolution of novel functional genes are the formation of regulatory regions that allow the expression of the genes and the effects of the new genes in the organism as well. Herein, we discuss the current knowledge on the evolution of novel functional genes, and we examine in more detail the youngest genes discovered. We examine the existing data on a very recent and rapidly evolving cluster of duplicated genes, the $Sdic$ gene cluster. This cluster of genes is an excellent model for the evolution of novel genes, as it is very recent and may still be in the process of evolving.

1. Introduction

The availability of complete genome sequences allows the comparison of genomes, thus revealing the differences in gene complement and demonstrating the nature of the changes that occur in the evolution of genomes. In particular, genomic analysis showed that more than one-third of the eukaryotic genome is composed of gene duplications and gene families (e.g., [1–4]), highlighting the prominence of duplications in the evolution of genomes. The study of whole genomes also allows an analysis of the rates and dynamics of duplications as well as the divergence and silencing of duplicates (e.g., [5–7]). Moreover, evidence indicates that the rates of duplication are extremely high and of the same order of magnitude as the rate of mutation per nucleotide; for example, the frequency of duplication for coding genes was found to be $0.01$ per gene per million years [8] and for internal duplications of gene segments, $0.001–0.013$ duplications/gene per million years [9].

The fates of gene duplicates can be very different according to the mutations they undergo and the selective pressures they are under. After a gene is duplicated, the most common fate seems to be the loss of function of one copy by the acquisition of degenerative mutations, while the other copy retains the original function. The originally identical copies can also both be maintained in the genome, allowing a higher production of the corresponding RNA or protein. Subsequent mutation by retrotransposon insertion into one of the copies can affect adaptive evolution because the effect on the phenotype can in some cases be beneficial to the organism [10]. Partial gene duplications can also occur, and if the duplicated part involves a structural or functional domain the new gene can increase the functional complexity of the encoded protein. It has also been proposed that if two copies of a gene acquire mutations in distinct subfunctions, the copies may undergo complementary loss of function in such a way that both copies are required to perform the original function; both copies would be maintained by selection [11]. Probably the most infrequent fate for a gene duplicate, and the one with most evolutionary impact, is for a duplicate copy to gain a new function by acquisition of mutations and to be maintained subsequently by selection while the old copy retains the original function. This last phenomenon leads to novel cellular functions and is the basis of the formation of divergent gene families. For a recent review of models of the evolution of gene duplications and the predictions for each model, see Innan and Kondrashov [12].

Gene duplication has long been thought to be a primary source of material for the evolution of new genes and new functions. The potential of gene duplication was first
recognized by Haldane [13], Bridges [14] and Muller [15]. In 1970, these ideas resurfaced with Ohno [16] who maintained that new genes and novel functions arise only by duplication and who presented evidence for the role of genome duplications in the evolution of multicellular organisms. Since then, the importance of duplications and of the divergence of duplicated copies has been widely supported (for a review see, e.g., [17–20]).

However, other evidence has accumulated showing that there are also other mechanisms responsible for the evolution of novel functions, such as exon shuffling, retroposition, gene fusion, and gene fission, and that several mechanisms can act together ([21–23] and recently reviewed in Kaessmann [24]). Another issue that has received attention is the formation of new regulatory regions, as these can be responsible for the development of novel expression patterns (for review see, e.g., [25–28]). In this paper, we will focus on the origin of very recent genes, which are of special interest since they may have not yet lost the signature of the events that took place during their formation, therefore conveying valuable information about those events.

2. Mechanisms of Origin of Novel Genes

The origin of novel genes has been extensively studied. In Table 1 is summarized the information on a sample of novel genes that reveals a picture of the events involved in their origin and their function. The sample is limited to genes that originated less than 50 million years ago to avoid confounding events of origination with effects of later evolution; this cutoff is also based on the dynamics of formation, preservation, and decay of duplicates and chimeras found by Rogers et al. [29]. Many of the novel genes described and characterized are from Drosophila species. The extensive work carried out on the evolution of new genes in Drosophila (see e.g., [30]) reflects the fact that D. melanogaster is a well-studied model organism at the molecular level that also has a long history of evolutionary studies.

Overall, there is no single mechanism of the molecular events involved in the formation and maintenance of novel genes, but rather several mechanisms. While gene duplication is conceded to have an important role in creating genetic novelties, an alternative mechanism for the origin of new genes is the shuffling of existing genes or functions to form chimeric genes. However, many chimeric genes derive from previously duplicated material, as shown by the presence of the parental genes in the genome and the organization of the chimeras found by Rogers et al. [29]. Many of the novel genes described and characterized are from Drosophila species. The extensive work carried out on the evolution of new genes in Drosophila (see e.g., [30]) reflects the fact that D. melanogaster is a well-studied model organism at the molecular level that also has a long history of evolutionary studies.

The contribution of chimeric genes to the evolution of genetic novelties has been revealed by recent studies. Rogers and colleagues [29, 31] compare the fate of simple genetic duplicates versus genetic duplicates that underwent fusion to form chimeras in D. melanogaster. The results are very interesting: gene duplications are formed at a rate of about 80.4 duplicates per million years, but only 4.1% are preserved; chimeras are formed at a rate of about 11.4 per million years and show a similar rate of decay (with 1.4% preservation) [29]. Some chimeric genes were also implicated in selective sweeps [31], revealing the impact of this kind of molecular event. This analysis of the D. melanogaster genome is interesting, but raises the question whether the same pattern would be observed in species that do not have such a high rate of DNA loss as D. melanogaster as found by Petrov and colleagues [33–35].

Equally relevant, and conceptually on the opposite side of the spectrum, is the origination of new genes "from scratch" or de novo, the case when coding sequences are derived from noncoding DNA, for example, introns and other untranslated regions [36–39]. This reutilization of noncoding sequences may have important consequences in the fate of such genes.

3. Tissues Where Novel Genes Are Expressed

Among the examples of new genes with very recent origin, many are involved in male reproduction, in particular in spermatogenesis. It is the case of Jingwei, which appears to be expressed in the testis [43]; Odyssey, which contains rapidly evolving homeodomains involved in sperm function [56]; Dntf-2r, which has male-specific expression [50]; K81, which is expressed in primary spermatocytes [58]; Sdic, whose product is incorporated into the sperm tail [47]. The prominence of expression in male reproductive tissue has led to the hypothesis that spermatogenesis is more prone to the cooption of novel genes and functions, while other developmental processes may be under a higher level of selective constraint [63]. As debated in Nielsen et al. [64], the testes undergo intense selection pressures because the cells are subject to genetic conflict, sperm competition, reproductive isolation and are exposed to germline pathogens and mutations that cause segregation distortion. An interesting observation in this regard is that newly retroposed duplicated genes in Drosophila are dominated by genes going from the X chromosome to the autosomes, not the opposite direction, and most of these have evolved a testis-specific expression pattern [65]. A possible explanation is that this predominantly one-way pattern is driven by positive selection because the retroposed genes escape X inactivation during spermatogenesis and are therefore free to develop expression patterns in the testis [65].

Kaessmann [24] emphasizes the importance of transcription during spermatogenesis, during which a permissive state of the chromatin may allow a widespread transcription of genes that would not otherwise be expressed. Additionally, during spermatogenesis, there are numerous cell divisions, affording an opportunity for new
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<tr>
<th>Gene</th>
<th>Mechanisms</th>
<th>Functions</th>
<th>Expression tissue</th>
<th>Species, genome location</th>
<th>Age (mys)</th>
<th>References</th>
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<tbody>
<tr>
<td>Monkey-king (mkg)</td>
<td>Duplication by retroposition and gene fission</td>
<td>Not determined</td>
<td>D. simulans/D. sechellia only males, D. mauritania males and females</td>
<td>D. simulans, D. sechellia, D. mauritania, X chromosome (chr.)</td>
<td>1-2</td>
<td>[23]</td>
</tr>
<tr>
<td>Quetzalcoatl</td>
<td>Duplication, gene fusion</td>
<td>Not determined</td>
<td>Early pupae, adult females, and male testes</td>
<td>D. melanogaster</td>
<td>&lt;2</td>
<td>[40]</td>
</tr>
<tr>
<td>Ifc-2h</td>
<td>Duplication by retroposition</td>
<td>Not determined</td>
<td>Whole body</td>
<td>D. simulans, D. sechellia, D. mauritiana</td>
<td>2</td>
<td>[41]</td>
</tr>
<tr>
<td>Hun</td>
<td>Exon shuffling by illegitimate recombination</td>
<td>Not determined</td>
<td>Testis</td>
<td>D. sechellia, D. mauritania, D. simulans</td>
<td>2-3</td>
<td>[42]</td>
</tr>
<tr>
<td>Jingwei</td>
<td>Exon shuffling, retroposition</td>
<td>Not determined</td>
<td>Testis</td>
<td>D. teissieri, D. yakuba, D. santomea</td>
<td>2-3</td>
<td>[43]</td>
</tr>
<tr>
<td>Sphinx</td>
<td>Exon shuffling, retroposition</td>
<td>Male courtship behaviour</td>
<td>Embryo, pupae, adult of males and females</td>
<td>D. melanogaster, chr. 4</td>
<td>2-3</td>
<td>[44, 45]</td>
</tr>
<tr>
<td>Poldi</td>
<td>De novo emergence from intergenic DNA</td>
<td>Involved in spermatogenesis, perhaps through chromatin modification pathways</td>
<td>Testis</td>
<td>Mus mus domesticus and four other species in the Mus genus.</td>
<td>2.5-3.5</td>
<td>[38]</td>
</tr>
<tr>
<td>Adh-Twain</td>
<td>Duplication, gene fusion</td>
<td>Not determined</td>
<td>Larvae, adult males and females</td>
<td>D. subobscura, D. guanche, D. madeirensis</td>
<td>3</td>
<td>[22, 46]</td>
</tr>
<tr>
<td>CG32582, CG32772, CG15323, CG32690, CG31909</td>
<td>From non-coding sequences</td>
<td>Not determined</td>
<td>Testis</td>
<td>D. melanogaster, D. simulans</td>
<td>2–5</td>
<td>[37]</td>
</tr>
<tr>
<td>Sflc</td>
<td>Duplication, gene fusion</td>
<td>Sperm competition</td>
<td>Testis</td>
<td>D. melanogaster, X chr.</td>
<td>&lt;5.4</td>
<td>[47–49]</td>
</tr>
<tr>
<td>Dntf-2r</td>
<td>Duplication by retroposition</td>
<td>Not determined</td>
<td>Testis</td>
<td>D. melanogaster, D. simulans, D. sechellia, D. mauritania, 2nd chr.</td>
<td>3–12</td>
<td>[50]</td>
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<tr>
<td>Nsr (kep1 gene family)</td>
<td>Duplication</td>
<td>Spermatogenesis</td>
<td>Testis (enriched in primary spermatocytes)</td>
<td>D. melanogaster subgroup, 2nd chr.</td>
<td>5.4–12</td>
<td>[51]</td>
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<td>CG3927 (kep1 gene family)</td>
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<td>Testis (enriched in primary spermatocytes)</td>
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<td>5.4–12</td>
<td>[51]</td>
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<tr>
<td>CG4021 (kep1 gene family)</td>
<td>Duplication</td>
<td>Spermatogenesis</td>
<td>Testis (enriched in primary spermatocytes)</td>
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<td>5.4–12</td>
<td>[51]</td>
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<tr>
<td>Sflc</td>
<td>Duplication</td>
<td>Male and female fertility, life expectancy</td>
<td>Not specified</td>
<td>D. melanogaster subgroup</td>
<td>6–11</td>
<td>[52]</td>
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<tr>
<td>Hydra</td>
<td>De novo emergence from intergenic DNA</td>
<td>Not determined</td>
<td>Testis</td>
<td>D. melanogaster subgroup</td>
<td>&lt;13</td>
<td>[53]</td>
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<tr>
<td>PIPS L</td>
<td>Exon shuffling, retrotransposition</td>
<td>Ubiquitin binding</td>
<td>Testis</td>
<td>Humans Chimpanzees</td>
<td>15–19</td>
<td>[54]</td>
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<tr>
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<td>Mechanisms</td>
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<tr>
<td>Odysseus (OdsH)</td>
<td>Duplication</td>
<td>Involved in sperm function</td>
<td>Mainly in male reproductive tissue, but also detected in larvae and embryo</td>
<td>D. melanogaster, D. simulans, D. sechellia, D. mauritana, D. yakuba</td>
<td>&lt;40</td>
<td>[56, 57]</td>
</tr>
<tr>
<td>K81</td>
<td>Duplication by retroposition</td>
<td>Telomere capping in postmeiotic male germ cells</td>
<td>Male specific expression (testis: primary spermatocytes), but weak expression also in wild-type females</td>
<td>D. melanogaster subgroup</td>
<td>&lt;30</td>
<td>[58, 59]</td>
</tr>
<tr>
<td>Obp57d and Obp57e</td>
<td>Duplication</td>
<td>Taste sensation of octanoic acid</td>
<td>Taste sensilla on the legs</td>
<td>D. melanogaster subgroup</td>
<td>&lt;30</td>
<td>[60, 61]</td>
</tr>
<tr>
<td>PGAM3</td>
<td>Exon shuffling, retroposition</td>
<td>Possibly phosphoglycerate mutase activity</td>
<td>White blood cells</td>
<td>Humans, chimpanzees, macaques, X chr.</td>
<td>&gt;25</td>
<td>[45, 62]</td>
</tr>
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mutations to arise, and those may affect sperm performance. Hence, spermatogenesis offers a large arena of competition in which cells and their descendants are under intensive selective pressure.

An important pattern observed in speciation, often considered the first step in the evolution of complete sterility and inviability, is Haldane’s rule, which states that, in an interspecific cross, if one sex is sterile or inviable, this sex is the heterogametic sex [66]. If novel genes appear more often in male reproductive tissue than in female reproductive tissue—as observed in the summary of novel genes in Table 1—this could be an explanation for Haldane’s rule when the heterogametic sterile F1 hybrid is the male, but not in the cases when it is the female. In Xenopus, in which males are the homogametic sex, males are always sterile in interspecific crosses [67]. However, while Xenopus seems an exception to Haldane’s rule, it may be a consequence of the fast evolution of male-specific genes. Strong sexual selection in males is reflected by rapid evolution of genes in male reproductive tissue, which then may cause hybrid sterility in recently diverged sister species even when males are homogametic. From this angle, tissue specificity of novel genes seems more important to hybrid sterility than heterogamy. It would be interesting to examine the tissue specificity of novel genes in species in which the female is the heterogametic sex, but this is beyond the scope of our paper.

4. The Sdic Gene Cluster

The Sdic gene is a recently evolved chimeric gene in D. melanogaster, discovered and described by Nurminsky and colleagues in 1998 [47, 68]. This gene possesses several unique features that provide an exceptional opportunity for the study of new gene functions, the fate of gene duplications, and the evolution of male reproductive traits.

Sequence analysis of the Sdic gene revealed that Sdic is a chimera of two genes that exist intact in the genome. Sdic is composed of parts of AnnX, which encodes an annexin protein, and Cdic (also referred to in the literature and FlyBase as sw), which encodes an intermediate polypeptide chain for the cytoplasmic dyneins [47]. The structure of Sdic along with the fact that AnnX and Cdic exist intact in the genome indicates that Sdic originated as a duplication and fusion of AnnX and Cdic, followed by small deletions and rearrangements. Its formation involved the creation of novel promoter elements (which provided testis-specific expression) from the fusion of portions of an AnnX exon and a Cdic intron. Its coding region, however, derived solely from Cdic. The comparison of the coding region of Sdic with Cdic shows that Sdic lacks the 3′ region of Cdic (which corresponds to 100 amino acids residues at the C-terminal part of the Cdic protein) and at its 5′ end underwent extensive refashioning by the occurrence of multiple mutations, deletions (including frameshift deletions), and insertions, culminating in a new 5′ exon that encodes a totally novel N-terminus for the protein [47, 69] (Figure 1).

There are several copies of Sdic located in tandem at the base of the X chromosome, in region 19 of the larval salivary gland polytene chromosomes, forming a gene cluster. This repeated region is flanked by the parental genes, on the 5′ side by Cdic and on the 3′ side by AnnX. According to the available genomic sequence of D. melanogaster, the Sdic gene is repeated four times in tandem between the genes Cdic and AnnX genes. Within this cluster there are also four dead-on-arrival retrotransposable elements of the RT1C family, one RT1C copy located upstream of each Sdic gene copy [70] (Figure 2).

Sdic is present in all wild-type strains of D. melanogaster [47], but it has not been found in any other species of the D. melanogaster subgroup. In the species closest to D. melanogaster (D. simulans, D. mauritiana, D. yakuba, D. teissieri, and D. erecta) AnnX and Cdic are adjacent to each other, without signs of an ancestral Sdic gene or RT1C element between them [71]. Furthermore, in these species, AnnX and Cdic do not show any signs of duplication and are reasonably conserved across species [71]. Consequently, the formation of the Sdic gene and the subsequent duplication that formed the entire cluster happened only in the lineage that gave rise to D. melanogaster; the original Sdic and the Sdic cluster were formed within the last 2 million years, after the split of the lineage that formed D. melanogaster and its sibling species D. simulans.

A model for the evolution of this cluster was developed based on the available genomic data [70], and the divergence of the RT1C copies, which are expected to be evolving neutrally, was used to date the duplications [48]. In the ancestral situation AnnX and Cdic must have been adjacent to each other. An initial event duplicated AnnX and Cdic, and then one or more deletions fused one copy of AnnX and one copy of Cdic giving rise to an ancestral Sdic. During the early steps of the formation of the ancestral Sdic, a dead-on-arrival retrotransposable element from the RT1C family was inserted upstream of the ancestral Sdic. The ancestral Sdic and its upstream region were duplicated in the last 232–463 thousand years, giving rise to two Sdic genes (and two RT1C, one upstream of each Sdic). Another duplication in the last 100–180 thousand years gave rise to four Sdic genes (and four RT1C, one upstream of each Sdic copy).

While the Sdic cluster has been isolated in the extremities of BAC clones, it is difficult to determine the overlap of the BAC sequences; moreover, there are nonassembled pieces of BAC clones containing Sdic portions that do not seem to match any of the assembled copies. The recent in situ hybridization work by Yeh et al. [49] indicates that all Sdic copies should be in region 19 of chromosome X. Given the young age of the cluster, the duplicates are predicted to be very recent and to have few or no differences in sequence, making it extremely difficult to confirm the exact number of genes by present sequencing and assembly techniques. The available sequences of assembled and nonassembled BAC clones could be explained either by four copies in tandem or eight copies that resulted from a duplication of preexisting four, yielding eight with the same pattern of similarities. The hypothesis of a cluster formed of four copies is the most parsimonious; however eight copies in tandem would be closer to the original Southern blot experimental results by Nurminsky et al. [47], which suggested as many as 10 duplicates.
One question still unanswered is that of the expression of the genes that belong to this cluster. Although the cluster is composed of four almost identical Sdic genes, there is no evidence for expression of all copies. The RNA sequences described in Nurminsky et al. [47] and Kulathinal et al. [63] are similar to what would be the expected transcription of Sdic1. Later work found evidence of expression for both Sdic1 and Sdic3 [49, 72]. Sdic1 is the oldest gene in the array and Sdic3 was originated from a duplication of Sdic1, being the second oldest. The promoter sequences of all copies are identical, except for the promoter of Sdic1, which differs from the others by two nucleotides. Although these changes at the promoter level might not be relevant, there is experimental evidence that the promoter of Sdic1, at least, is a functional promoter: Nurminsky et al. [47] tested the Sdic1 promoter in vivo and in vitro and found it to be functional.

The presence of extra genetic material in the Sdic region when one compares D. melanogaster with the other species of the D. melanogaster subgroup, extra material that contains a cluster of nearby identical genes and dead-on-arrival transposable elements is remarkable. D. melanogaster has a high rate of gene loss of unessential genetic material caused by deletions [33–35]. Additionally, according to existing models of the fate of gene duplicates and in light of the high rate of nonessential DNA loss in D. melanogaster, if not all copies of Sdic are functional then one would predict that the extra copies of Sdic would be in the process of degeneration showing many deletions and mutations in the coding sequences as well as the RT1C elements. However, the Sdic copies and RT1C elements appear very similar to each other. It is possible that, given the young age of the cluster, degeneration is in such early stages that such mutations have not occurred or that those that may have occurred have been repaired by gene conversion from nonmutated copies. It is also possible that the Sdic cluster has important cellular functions yet to be discovered. Novel gene functions are frequently associated with rapid changes and show signs of positive selection [44, 50, 73], supporting the idea that novel genetic functions allow adaptive changes. There is limited evidence for positive selection of Sdic and at least one selective sweep in this region [47, 63, 74].

A key question concerning any novel gene and the functional role it fulfills is whether the function itself is novel or whether the function is redundant or overlapping with an already existing functional gene or genes. The function of Sdic protein was deduced from its sequence to be a sperm-specific dynein intermediate chain, and this deduction was supported by the finding of the Sdic1 gene product in the sperm tail [47]. Is the Sdic protein redundant with another sperm dynein intermediate chain or has it supplanted a pre-existing gene? Has Sdic played a role in the speciation events in the split of the lineage of D. melanogaster from its sibling
species and has Sdic had an effect in adaptation or sexual
selection in D. melanogaster?

These questions on the role of Sdic have been addressed
very recently in experiments in which Yeh and colleagues [49]
knocked out the Sdic region in D. melanogaster and looked
for phenotypic effects on male reproduction. While no effects
were detected in progeny size or sex ratio, males without Sdic
had sperm that were less competitive in the female repro-
ductive tract in being more easily displaced by sperm from
subsequent males and, to a lesser extent, in being less able to
displace sperm from previous males. These results support
the role of the Sdic protein in sperm competition, but most
importantly they answer the central question for new
genes of “how did the sibling species manage without this
function?” the work by Yeh et al. [49] shows that Sdic plays
an important role in reproduction, and although it is not an
essential gene, it gives an advantage in sperm competition,
which could in turn be related to the positive selection.

It remains to be determined whether positive selection
has acted upon all copies of Sdic and if the copies are sub-
jected to the same selective pressures, but the importance of
this gene cluster in reproduction has at least been demon-
strated, and the results may help to shed light on the general
issue of the function of novel genes

5. Concluding Remarks

Ultimately, differences observed between species are due
to differences at the genome level. Genomic studies are
revealing the extent of these differences—in gene number,
in encoded functions, in expression—and are also revealing
the mechanisms involved in the evolution of genomes. The
analysis of particular newly evolved genes provides infor-
mation in finer detail, which hopefully can be generalized
and help to understand the evolution of new genes and new
functions. Equally as important as the formation of new
coding sequences is the formation of regulatory regions
responsible for new patterns of expression as well as the pro-
cesses leading to spread and maintenance of the novel gene
in the population.

Bacterial genome studies have made very clear that, at
least in bacterial species, a great part of the genes are not
shared by all individuals of a species [75]. Different strains
of the same species share a core genome containing genes
present in all strains; however there is also a pan-genome
consisting of genes present in only a subset of strains. As
more complete genome sequences become available, we will
be able to determine if similar patterns are observed in
eukaryotes.

Author’s Contribution

R. Ponce and L. Martinsen contributed equally to this work.

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