Design of Novel Adaptive Routing by Mimicking Enzymic Feedback Control Mechanism in the Cell

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ABSTRACT

The routing algorithm of SPF (Shortest Path First) [1] is widely distributed in large scale network such as internet. Since this routing algorithm is designed in order to improve throughput of each packet which is sequentially generated at the nodes, it is not suitable for averaging load balance in the network. The enzymic feedback in the cell is the typical and basic control mechanism which can realize homeostasis of the value of every reactant in the metabolic pathway. The purpose of this study is to design an adaptive routing in which the packets generated at the nodes can be sent to the final destinations with avoiding the partial and time-variant traffics in the network, and the load balance in the network can be averaged. We have proposed here a new adaptive routing algorithm by introducing an enzymatic feedback control mechanism in the cell.

Keywords: Adaptive routing, Biomimetics, Enzymatic feedback, Homeostasis and Fault-tolerant network topology

1. INTRODUCTION AND BACKGROUND

The metabolic pathway in the cell is so-called "a stream of water" and is composed of a lot of enzymic reaction steps in which reactant (substrate) is converted to the product by unique "enzyme" (catalyzed protein), and the produced product is converted to the product by enzyme at the subsequent reaction step and so on. Enzymes are proteins which catalyze the turnover of substrates without being consumed themselves and without changing the equilibrium of the biochemical reaction. In metabolic pathways, the product of a late (or the last) step frequently acts as an inhibitor of the first committed step in this pathway ("negative feedback control"). This way, the end product of a pathway controls its own synthesis and prevents useless accumulation of intermediates. Enzymic feedback control can be considered to be a bandwidth control; rate velocity of consumption of substrate can be represented by the function of substrate (A) and feedback inhibitor (B). There are so many function mechanisms of feedback control in the cell, however, for example, when the B is assumed to control the rate velocity of A with a manner of competitive inhibition [2] (one of the feedback functions), the rate velocity of A (d[A]/dt, t represents time) can be mathematically written as follows:

$$\mathrm{d[A]/dt} = -\frac{V\max[A]}{Km(1+[B]/Ki)+[A]} \qquad (1)$$

where *Vmax* represents maximum velocity (reaction rate) of enzyme activity, *Km* is the value of substrate giving 0.5*Vmax*, *Ki* is the feedback coefficient. Anyway, d[A]/dt is the function of the substrate A and the feedback inhibitor B. In the case of accumulation of B, the absolute value of the term in the right-side of eq.(1) become to be small. Since the B is the end product of the pathway, we can easily considered that the accumulation of B corresponds to be "traffic" of the pathway; the absolute value of the term in the right-side of eq.(1) represents new metric of "traffic" from the view point of network routing. Thus, in this study, we define the following metric of routing by mimicking enzymic feedback control in the cell:

$$k = p / V\max \qquad (2)$$

$$p = \frac{V\max[a]}{Km(1+[b]/Ki)+[a]} \qquad (3)$$

where [a] represents the reserved sending packet size (Byte) to the nearest node, [b] is the total accumulated packet size (Byte) at the nearest node, *Vmax* is maximum sending rate (Mbps), and *Km* and *Ki* are the arbitrary coefficients. The value of k in eq.(2) decreases with the increase in "traffic". Furthermore, we define the following weighted multi-objective *f*:

$$f = (1-\alpha)k + \alpha(1/h) \qquad 0<\alpha<1 \qquad (4)$$

where α represents arbitrary coefficient; if α=1, the network routing will be performed according to the SPF (Shortest Path First) algorithm.

At the branching of node-pathways, the value of *f* at each branching pathway is calculated and it determines the node to be sent with having the larger value of *f*. This is the outline of the proposed dynamic adaptive routing algorithm where most of the packets will be sent to the final destination with escaping from the traffic nodes; the QOS (quality of service) of the proposed algorithm is expected to be "averaging the load within the network".

2. CASE STUDY AND VALIDATION

The following node-network was used in order to evaluate our algorithm, where the numeral (0 to 5) represents the node-number, and the bold line is the connection pathway between nodes:

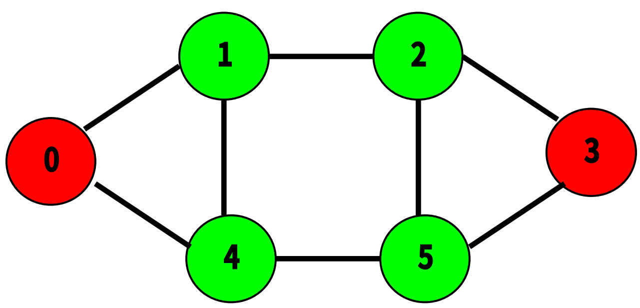

Fig. 1 6 nodes-network

Supposing the three kinds of sequential packets to be sent randomly in the network (total number of packets is 300); one is the packets generated at the starting node 0 and sent to the destination node 3, second is those generated at the starting node 0 and sent to the destination node 2, and the last one is those generated at the starting node 0 and sent to the destination node 5. Each packet has 3072B size and is generated at every 150 μsec. The maximum sending rate between binding nodes is fixed at 100Mbps. The control packet (64B) is sending to the nearest node at every 5000 μsec. This control packet involves the information of the value of [b] (total accumulated packet size) in eq.(3). The time between the generating and arriving at the final destination (passage) of every packet and transient sending route of every packet were examined. The default route was supposed to be 0 → 1 → 2 → 3 for the packets sending to the node 3 and to be 0 →1→ 2 for the packets sending to the node 2 and to be 0 → 4 → 5 for the packets sending to the node 5 ; the route 0 → 1 → 2 is overlapped which will lead to the traffic of the packets at this route.

For comparison, the passage profile with packets to be sent was examined in the case of SPF algorithm; every packet is sent to the final destination according to the default route. The results can be summarized as follows: As shown in Fig. 2, the passage increases with the packet ID that means the traffic is occurred at the route between the nodes 0 and 2.

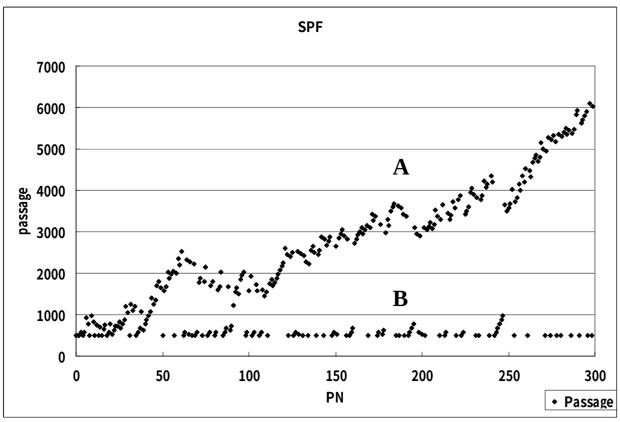

Fig. 2 Passage profile with packet by using SPF algorithm. The abscissa and the ordinate represent data packet ID and passage (μsec), respectively. A, packet sending to the nodes 2 and 3; B, packet sending to the node 5.

Fixed the value of α in eq.(4) at 0.5, the passage profile with packets to be sent was examined by introducing our proposed algorithm. The results are shown in Fig. 3. Also the passage profiles for the packets sending to the node 3 and for those sending to the node 2 and for those sending to the node 5 are shown in Figs. 4, 5 and 6, respectively. The average, minimum and maximum passage of Figs. 2 and 3 are summarized in Tables 1 and 2, respectively. Those of Figs. 4, 5 and 6 are also summarized in Tables 3, 4 and 5, respectively.

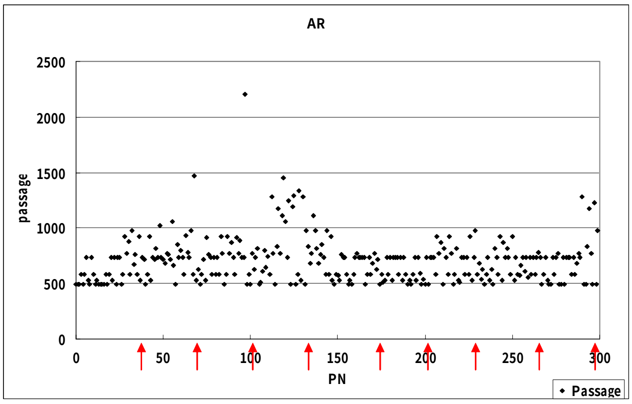

Fig. 3 Passage profile with packet by using the proposed routing algorithm. The abscissa and the ordinate represent data packet ID and passage (μsec), respectively. The arrow shows the time-point when the control packet was sent to the nearest node.

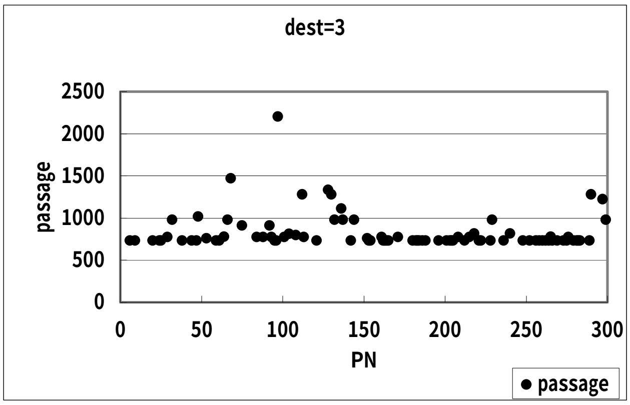

Fig. 4 Passage profile with packet sending to the node 3 by using the proposed routing algorithm. The abscissa and the ordinate represent data packet ID and passage (μsec), respectively.

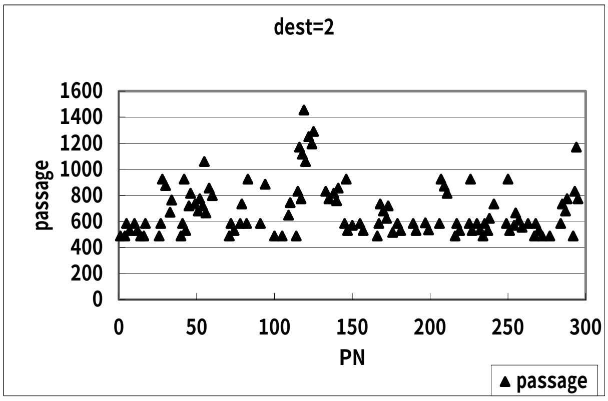

Fig. 5 Passage profile with packet sending to the node 2 by using the proposed routing algorithm. The abscissa and the ordinate represent data packet ID and passage (μsec), respectively.

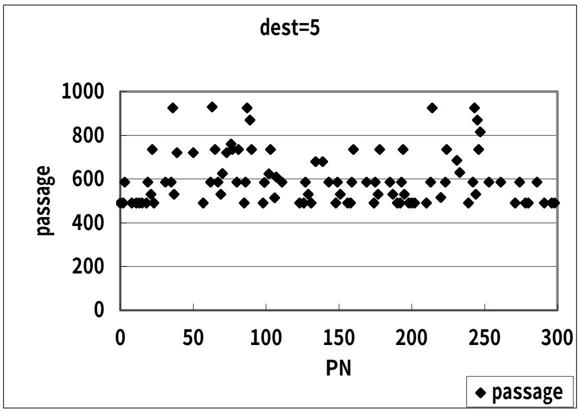

Fig. 6 Passage profile with packet sending to the node 5 by using the proposed routing algorithm. The abscissa and the ordinate represent data packet ID and passage (μsec), respectively.

Table 1 Summary of passage profile shown in Fig. 2.

Total number of data packets	300
Average of passage (μsec)	2129
Standard deviation of passage	1592
Minimum passage (μsec)	490
Maximum passage (μsec)	6090

Table 2 Summary of passage profile shown in Fig. 3.

Total number of data packets	300
Average of passage (μsec)	702
Standard deviation of passage	206
Minimum passage (μsec)	490
Maximum passage (μsec)	2205

Table 3 Summary of passage profile shown in Fig. 4.

Total number of data packets	89
Average of passage (μsec)	831
Standard deviation of passage	217
Minimum passage (μsec)	735
Maximum passage (μsec)	2205

Table 4 Summary of passage profile shown in Fig. 5.

Total number of data packets	114
Average of passage (μsec)	688
Standard deviation of passage	201
Minimum passage (μsec)	490
Maximum passage (μsec)	1455

Table 5 Summary of passage profile shown in Fig. 6.

Total number of data packets	98
Average of passage (μsec)	601
Standard deviation of passage	123
Minimum passage (μsec)	490
Maximum passage (μsec)	930

As shown in Figs. 2 and 3, and Tables 1 to 5, most of the passages of data packets were averaged, which means that our proposed algorithm is effective for dynamic adaptive routing. According to Figs. 2 and 3, part of the transient passage profiles of packets and route sending to the final destination by using SPF algorithm and by using the proposed algorithm are summarized in Tables 6 and 7, respectively.

In Table 7, the shadowed columns represent the packets which were sent by using the non-default routes (default routes are 0→1→2→3 for the packets sending to the node 3, 0→1→2 for those sending to the node 2, and 0→4→5 for those sending to the node 5). In Table 7, most of the packets sending to the node 2 or 5 were sent by using the default route, however, focused on the packets between 242 and 247 their routes are flexible such as 0→4→5, 0→1→4→5 and 0→1→2→5 with escaping from the traffic nodes. The routes for the packets sending to the node 3 are most flexible; the route 0→4→5→3 is another short-cut route and the routes 0→1→4→1→2→3 and 0→1→4→5→3 are alternative ones with escaping from the traffic nodes. Since the maximum sending rate between all binding nodes is fixed at 100Mbps and the each data packet size is 3072B, the minimum required time sending to the nearest node is 245μsec (minimum required time sending from the node to the node 3 is 245 x 3 = 735μsec). The passages for PID=290, 297 and 299 are 1280, 1225 and 980μsec, respectively, which were near to 245 multiplied by the number of hops; 1280 is approximately equal to 245 x 5, and 1225 and 980 are quite equal to 245 x 5, 245 x 4, respectively. These results show the proposed algorithm can find alternative non-traffic routes with considering the smaller number of hops to the destination.

Even if each packet arrives at the final destination with escaping from the traffic nodes, it is key issue that all packets, which constitute one data-file, arrive at the final destination in the order of sending from the starting node. For example, when the packet 3 arrives at the final destination prior to the packets 1 and 2, sorting process can not be performed until both of these packets arrive. In the case where this waiting time is larger than a given threshold value, routing system should request to the sending node for re-sending of packets. In the 6-node network shown in Fig. 1, we examined the waiting time at the final destinations (node 2, 3 and 5). The simulation conditions are as follows: (1)three kinds of sequential packets to be sent randomly from node 0. (2)total number of packets is 300, and the number of packets to the nodes 2, 3 and 5 is 100, respectively. (3)each packet has 3072B size and is generated at every 125 μsec. Figure 7 shows the histogram of waiting time at the node 3 when the weighting coefficient α in eq. (4) is fixed at 0.5. The ordinate represents the relative frequency at each class. The abscissa shows class of histogram, for example, 1000 and 2000 means 0-1000μsec and 1001-2000μsec, respectively. Figure 7 shows the average of 10 trails. Next we change in α value according to the following algorithm and examined waiting time with the same conditions above:

$$
\begin{aligned}
&if\,(sHop > Cnt)\\
&\alpha = 0.5\\
&if\,(sHop \le Cnt < 2sHop)\\
&\alpha = 0.5 + \frac{0.2}{sHop} \times (Cnt - sHop) \qquad (5)\\
&if\,(Cnt > 2sHop)\\
&\alpha = 0.7
\end{aligned}
$$

where, *sHop* and *Cnt* represent the number of the shortest hops from stating node to the final destination node, and the accumulated number of nodes for the packet to pass through, respectively.

Table 6 Transient passage profiles of packets by using SPF algorithm.

Packet ID	generate	arrive	passage	route
240	36150	40500	4350	0>1>2>3
241	36300	40500	4200	0>1>2
242	36450	36940	490	0>4>5
243	36600	37185	585	0>4>5
244	36750	37430	680	0>4>5
245	36900	37675	775	0>4>5
246	37050	37920	870	0>4>5
247	37200	38165	965	0>4>5
248	37350	40990	3640	0>1>2>3
249	37500	40990	3490	0>1>2
250	37650	41235	3585	0>1>2
251	37800	41480	3680	0>1>2
252	37950	41970	4020	0>1>2>3
275	41400	46625	5225	0>1>2>3
276	41550	46870	5320	0>1>2>3
277	41700	46870	5170	0>1>2
278	41850	42340	490	0>4>5
279	42000	47360	5360	0>1>2>3
280	42150	42640	490	0>4>5
281	42300	47605	5305	0>1>2>3
282	42450	47850	5400	0>1>2>3
283	42600	48095	5495	0>1>2>3
284	42750	48095	5345	0>1>2
285	42900	48340	5440	0>1>2
286	43050	43540	490	0>4>5
287	43200	48585	5385	0>1>2
288	43350	48830	5480	0>1>2
289	43500	49320	5820	0>1>2>3
290	43650	49565	5915	0>1>2>3
291	43800	44290	490	0>4>5
292	43950	49565	5615	0>1>2
293	44100	49810	5710	0>1>2
294	44250	50055	5805	0>1>2
295	44400	50300	5900	0>1>2
296	44550	45040	490	0>4>5
297	44700	50790	6090	0>1>2>3
298	44850	45340	490	0>4>5
299	45000	51035	6035	0>1>2>3

Table 7 Transient passage profiles of packets and the route sent to the final destination by using the proposed algorithm

Packet ID	generate	arrive	passage	route
240	36151	36966	815	0>1>2>3
241	36301	37036	735	0>4>1>2
242	36451	37036	585	0>4>5
243	36601	37526	925	0>1>4>5
244	36751	37281	530	0>4>5
245	36901	37771	870	0>4>5
246	37051	37786	735	0>1>2>5
247	37201	38016	815	0>4>5
248	37351	38086	735	0>1>2>3
249	37501	38086	585	0>1>2
250	37651	38576	925	0>4>1>2
251	37801	38331	530	0>1>2
252	37951	38686	735	0>4>5>3
275	41401	42136	735	0>1>2>3
276	41551	42326	775	0>4>5>3
277	41701	42191	490	0>1>2
278	41851	42341	490	0>4>5
279	42001	42736	735	0>1>2>3
280	42151	42641	490	0>4>5
281	42301	43036	735	0>1>2>3
282	42451	43186	735	0>4>5>3
283	42601	43336	735	0>1>2>3
284	42751	43336	585	0>1>2
285	42901	43636	735	0>4>1>2
286	43051	43636	585	0>4>5
287	43201	43881	680	0>1>2
288	43351	44126	775	0>1>2
289	43501	44236	735	0>4>5>3
290	43651	44931	1280	0>1>4>1>2>3
291	43801	44291	490	0>4>5
292	43951	44441	490	0>1>2
293	44101	44931	830	0>1>2
294	44251	45421	1170	0>4>1>2
295	44401	45176	775	0>1>2
296	44551	45041	490	0>4>5
297	44701	45926	1225	0>1>4>1>2>3
298	44851	45341	490	0>4>5
299	45001	45981	980	0>1>4>5>3

For example, in the case of packets generating at the node 0 and sending to the node 3, *sHop* is 3 and when *Cnt* is over 3, α value increases linearly to 0.7 with the *Cnt*; α value is 0.7 at $Cnt = 2sHop$ (6 in this case) and fixed at 0.7 when *Cnt* is over 2*sHop*. Figure 8 shows the histogram of waiting time where α value is variable according the above schedule.

Compared Fig. 8 with Fig. 7, changing in α value is efficient method for reducing the waiting time; in Fig. 7, the sum-up of relative frequency at the classes over 4000 is 16.1%, whereas in Fig. 8, the corresponding frequency is 0%.

3. DISCUSSION

The OSPF (Open Shortest Pass First) [3] is the routing protocol by using various cost parameters as metrics; the

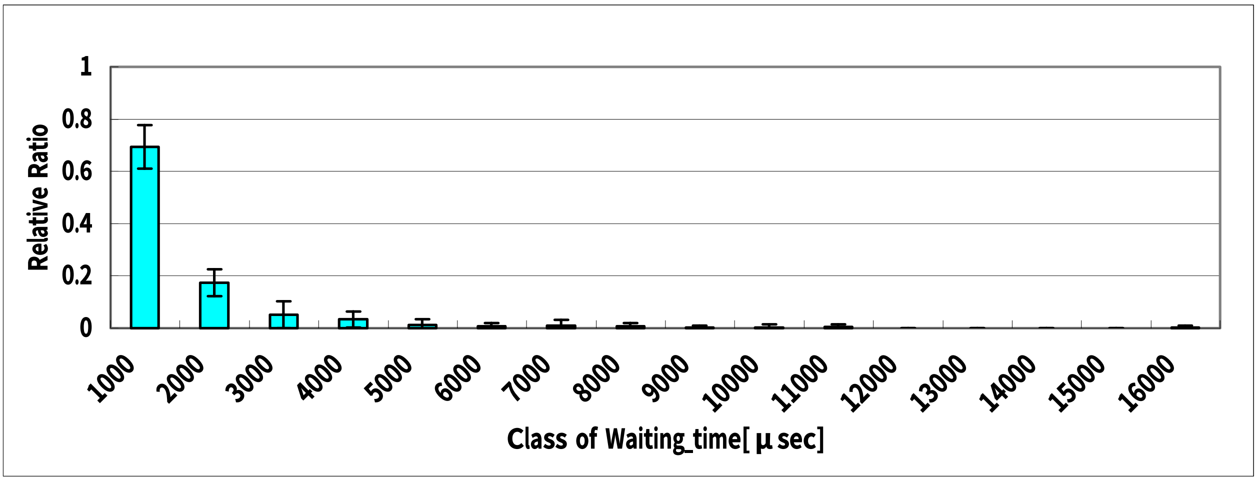

Fig. 7 Histogram of Waiting_time at the node 3 under fixing the α value in eq.(4) at 0.5.

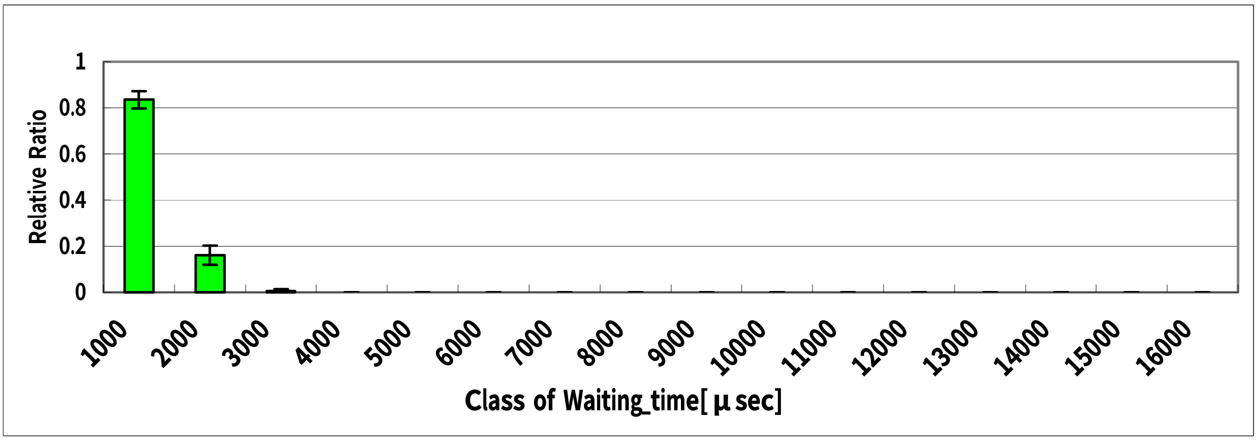

Fig. 8 Histogram of Waiting_time at the node 3 under the condition where theα value changes with schedule (5).

followings are considered to be cost parameter: reliability, delay, bandwidth, load, maximum transfer unit, communication cost. In this study, we proposed here eqs. (2), (3) and (4) by mimicking the mechanism of enzymatic feedback function in the cell. As shown in eq. (3), the p is the integrated parameter considering both the current traffic status between the self-node and the nearest bonding node (the [a] in eq. (3) numerically reflects this information) and the most recent traffic status between the nearest bonding node and the subsequent nodes (the [b] in eq. (3) numerically reflects this information). The Km represents the [a] value giving the half speed of maximum sending rate (*Vmax*); the smaller *Km* value gives the steeper decrease of p-value. The *Ki* determines steepness of the *p*-value *vs*. [a]-value; the smaller *Ki* value represents the stronger feedback control. In metabolic pathways in the cell we can observe various kinds of feedback function mechanisms except for eq. (1) or (2) [2]. These functions including eq. (3) have high possibility to be acceptable as new metrics in OSPF.

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