Performance Analysis on Negligible Blocking DC-based Optical Switching Networks Under Crosstalk Constraint

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Summary
Banyan networks are attractive for serving as the optical switch architectures due to their nice properties of small depth and absolutely signal loss uniformity. Banyan structure is one of the candidates for serving as the directional-coupler (DC)-based switching systems that can switch signals at the rate of several terabits per second. Despite many advantages, optical banyan networks suffer from an intrinsic crosstalk problem that must be overcome in building a robust switching system. Vertical stacking of multiple copies of an optical banyan network is a novel scheme for building nonblocking optical switching networks. The resulting network, namely vertically stacked optical banyan (VSOB) network, preserves all the properties of the banyan network, but increases the hardware cost significantly under first order crosstalk-free constraint. Blocking behavior analysis is an effective approach to studying network performance and finding a graceful compromise among hardware cost, crosstalk tolerance and blocking probability. Little is known on analyzing the blocking behavior in such VSOB networks with some degree of crosstalk constraint.
In this paper, the implementation of constructing negligible blocking VSOB networks under various small degree crosstalk constraints will be presented. We find how crosstalk adds a new dimension to the performance analysis on a VSOB network. We implement the possible upper bound on blocking probability which can describe the overall blocking behavior in VSOB networks. The numerical results implanted in the paper can guide network designer in finding the tradeoff among the blocking probability, the degree of crosstalk and the hardware cost in terms of vertical copies of Banyan network.

Key words:
Optical switching networks, vertically stacked banyan networks, blocking probability, crosstalk.

Introduction

Optical mesh networks are considered more capacity-efficient and survivable for serving as the backbones for next generation Internet. A key network element equipped with a switching node of optical mesh networks is the optical switch, which has the capability of switching huge data at an ultra-high speed. The basic 2×2 switching element (SE) in a large optical switching network is usually a directional coupler (DC) [9][13]. DC's can switch multiple wavelengths at same time, which is important for the future optical cross-connects (OXCs).

Crosstalk is an intrinsic shortcoming of the DC. It is the effect of the undesirable coupling between the signals carried in the two waveguides of the coupler [9,14]. When two optical signals meet at a DC, a small portion of the signal power will be directed to the unintended output channel. Crosstalk suppression becomes particularly important in networks, where a signal propagates through many nodes and accumulates crosstalk from different elements at each node from the system view. In order to obtain an approximate idea of the crosstalk requirements, suppose that a signal accumulates crosstalk from N sources, each with crosstalk level ε. This neglects the fact that some interfering channels may have higher powers than the desired channel. Networks are very likely to contain amplifiers and to be limited by signal-spontaneous beat noise. For example, if we have 10 interfering equal-power crosstalk elements, each producing intrachannel crosstalk, then we must have a crosstalk suppression of below 35dB in each element, in order to have an overall penalty of less than 1 dB [13]. Thus, crosstalk reduction is an important issue in designing the systems that are based on DC's. The crosstalk issue can be tackled at either the device level or the system level. The two methods complement each other. The focus of this paper is on the system-level approach. As will be seen, crosstalk adds a new dimension to the theory of building a nonblocking and negligible blocking switching network.

Banyan networks [4,6,8,10] are a class of attractive switching structures for constructing DC-based optical switches, because they have a smaller and exact same number of SEs along any path between an input-output pair such that an absolutely loss uniformity and smaller attenuation of optical signals are guaranteed in this class of switching networks. However, with the banyan topology only a unique path can be found from each network input to each network output, in which the network is degraded as a blocking one. The general scheme for building banyan-based nonblocking optical switching networks is to vertically stack the multiple copies of regular optical banyan network [7,11] as illustrated in Fig.1.

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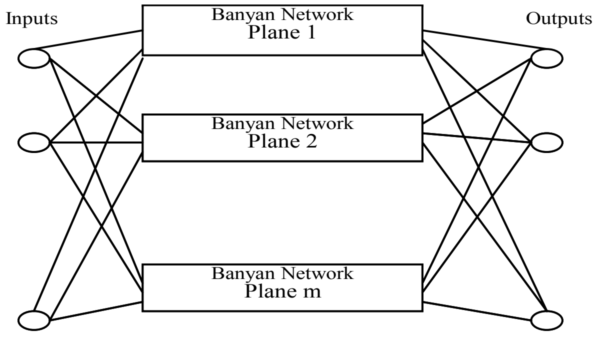

Fig.1 Illustration of the vertical stacked optical banyan network.

There is, however, another type of blocking in DC-based photonic switching systems. Sometimes, all the links along the path of the new connection are available, but adding the connection will violate the specified crosstalk constraint along the path of the new or an existing connection. Under such condition, the new connection will still be blocked even though the path is available. This is called crosstalk-blocking throughout the paper. It is the combination of the two types of blocking that makes the design principle different.

We use VSOB to denote the optical switching networks built on vertical stacking scheme of banyan network. In order to theorize the affection of degree of crosstalk and blocking probability in VSOB network, in this paper, we focus on the implementation of overall blocking behavior in VSOB network under some certain degree of crosstalk constraint.

Numerous result are available for VSOB networks, such as [7,11,12], and their main focus has been on determining the minimum number of stacked copies (planes) required for a nonblocking VSOB network. These results indicate that VSOB structure, although is attractive, usually requires either a high hardware cost or a relatively larger depth for building a nonblocking network.

Blocking behavior analysis of a network is an efficient approach to studying network performance and finding desirable trade-off between hardware costs and blocking probability. Some analytical models have been developed to understand the blocking behaviors of vertical stacked optical banyan networks that do not meet the nonblocking conditions under crosstalk-free constraint (i.e., with fewer stacked copies than required by nonblocking condition)[15,16,17]. To our best knowledge, however, no results are available for evaluating the probabilities of VSOB networks under various degree of crosstalk constraint. As the first important step toward the blocking behavior analysis of general VSOB networks under any crosstalk constraint, we implemented in this paper the blocking probabilities of VSOB networks under crosstalk constraint with c=1, 2, and 3, which c is denoted to the degree of crosstalk, and implement their upper bound with respect to the number of planes in the networks. The implementation results can guide networks designers to initiate a compromise among the hardware cost and the blocking probability in a VSOB network under different degree of crosstalk. In particular, our implementation is useful for estimating the maximum blocking probability of a VSOB network in which different routing strategies might be applied.

The rest of the paper is organized as follows: Section II provides preliminaries that facilitate our further discussions and implementation. Section III introduces the proposed analysis and implementation for the VSOB networks. Section IV presents the implemented results, which are compared and verified with that yielded by the proposed and previous research results. Section V concludes the paper.

2. Preliminaries

A typical $N \times N$ banyan network consists of $\log N$* stages, each containing $N/2$ 2×2 SEs. Regular banyan network has a unique path between an input-output pair, and a basic technique for creating multiple paths between an input-output pair is the vertical stacking of multiple copies of the banyan network. In this paper, we focus on the banyan network that has m multiple copies as shown in Fig.2.

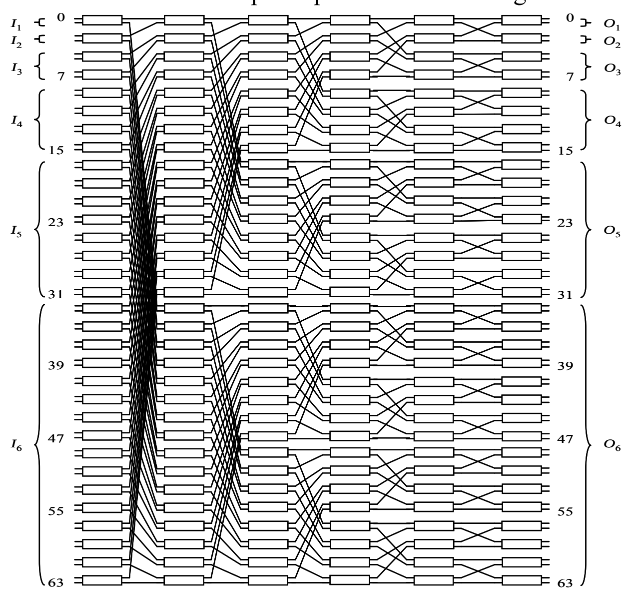

Fig.2 64×64 banyan network.

Due to their symmetry structures, all paths in a banyan networks have the same property in terms of blocking. We

* In this paper log means the logarithm to the base 2.

define the blocking probability to be the probability that a feasible connection request is blocked, where a feasible connection request is a connection request between an idle input port and an idle output port of the network. Without loss of generality, we chose the path between the first input and the first output (which is termed as the tagged path in the following context) for blocking analysis. All the SEs on the tagged path are called tagged SEs. The stages of SEs are numbered from left (stage 1) to right (stage log*N*). For the tagged path, an input intersecting set I_i associated with stage *i* is defined as the set of all inputs that intersect a tagged SE at stage *i*. Likewise, an output intersecting set O_i associated with stage *i* is the set of all outputs that intersect a tagged SE at stage log*N*-*i*+1.

When two light signals go through an SE simultaneously, crosstalk is generated at the SE. Such SE is referred to as a crosstalk SE (CSE). The degree of crosstalk of the switching system is defined as the number of CSE's allowed along a path. The crosstalk generated at each CSE can be found in the data sheet from the manufacturer.

A restricted SE (RSE) is a 2×2 SE which carries only one light signal at a time. Although crosstalk at an RSE is very small, it may not be entirely zero. For example, when a light signal passes through an RSE, a small portion of the signal will leave at the other unintended output channel. This stray signal can arrive at the input of the next stage SE and generate some crosstalk. Since crosstalk generated by the stray signal is much smaller than the regular crosstalk, we will ignore it in our analysis [11].

Following the typical assumption as in [15,16] on probabilistic analysis of multistage interconnection networks, we neglect the correlation among signals arriving at input and outputs ports, and consider that the statuses (busy or idle) of individual input and output ports in the network are independent. This assumption is justified by the fact that the correlation among signals at inputs and outputs, though exists for fixed communication patterns, and becomes negligible for arbitrary communication patterns in large size networks, which is the trend of future optical switching networks that can switch huge data at high speeds.

3. Performance Analysis on VSOB Networks

3.1 Deterministic Condition for Strictly Nonblocking

For simplicity, we use VSOB(*N*,*m*,*c*) to denote an *N*×*N* VSOB network that has *m* stacked copies (planes) of an *N*×*N* banyan network allows *c* CSEs along the path. To get an upper bound on the blocking probability of a VSOB(*N*,*m*,*c*) network, we consider a "conservative " routing control strategy, in which each of these connections that block a specified tagged path (out of two tagged paths) in a VSOB(*N*,*m*,*c*) should be a in distinct plane to guarantee the nonblocking property. Here, we define a plane of VSOB(*N*,*m*,*c*) as a blocked plane if its tagged path is blocked.

In this section, we will briefly describe the deterministic condition for the strictly nonblocking VSOB(*N*,*m*,*c*) network that is obtained based on the worst-case analysis. Then develop our conservative routing control strategy to get the possible maximum blocking probability based on the deterministic condition.

Lemma 1: A VSOB(*N*,*m*,*c*) network with even log*N* stages is strictly nonblocking if the following is true:

$$m \geq \begin{cases} \frac{3}{2}\sqrt{N} + \left\lfloor \frac{1}{c+1}\sqrt{N} \right\rfloor - 1, & \text{if } 0 < c \leq \frac{1}{2}\log N \\ \frac{3}{2}\sqrt{N} - 1, & \text{if } \frac{1}{2}\log N < c < \log N \end{cases}$$

When logN is odd, the condition becomes the following:

$$m \geq \begin{cases} \sqrt{2N} + \left\lfloor \frac{1}{c+2}\sqrt{2N} \right\rfloor - 1, & \text{if } 0 < c \leq \frac{1}{2}(\log N - 1) \\ \sqrt{2N} + \left\lfloor \frac{1}{2(c+2)}\sqrt{2N} \right\rfloor - 1, & \text{if } \frac{1}{2}(\log N - 1) < c < \log N \end{cases}.$$

Illumination: Considering about the crosstalk constraint by allowing *c* CSE's along the path of a connection. The nonblocking conditions for the networks are examined as a function of c. In this case, both link-blocking and crosstalk-blocking can occur. The condition for strictly nonblocking networks under a specific crosstalk constraint will be bounded by the results in [11].

Consider the case when log*N* is even. We can easily find that in this case, each input from sets I_1 through $I_{(1/2)\log N-1}$ and each output from sets O_1 through $O_{(1/2)\log N-1}$ can block the tagged path regardless of the type of blocking—link-blocking or crosstalk-blocking. This is in fact the case for any arbitrary *c*. Thus, in the worst-case condition, we assume that each of them can block a separate plane. If the network is only a link-blocking network, then the connections originating from $I_{(1/2)\log N}$ must be destined for $O_{(1/2)\log N}$ and the number of planes blocked by them is only half the total number of elements in the two sets. With crosstalk-blocking, connections from $I_{(1/2)\log N}$ to $O_{(1/2)\log N+1}$ and connections from $I_{(1/2)\log N+1}$ to $O_{(1/2)\log N}$ can be blocked by adding the new connection. If there are *y* connections in each case, we will have in total of 2*y* connections blocked due to crosstalk violations. The rest of the elements in $I_{(1/2)\log N}$ and $O_{(1/2)\log N}$ can still cause link-blocking. As a result, we need the total of *y* additional planes to take care of crosstalk-blocking.

We now determine *y*. Equivalently, we want to determine how many connections can be established from $I_{(1/2)\log N}$ to $O_{(1/2)\log N+1}$ that have *c* CSE's along their path. First, we consider the case where $1 \leq c \leq (1/2)\log N$. For such a connection, the CSE's occur at stages (1/2)log*N*+1 through log*N* corresponding to the worst-case condition. If not, one element from $I_{(1/2)\log N}$ will be used to generate the CSE and thus reduce the number of possible intersecting connections. Therefore, we conclude that $y = \lfloor \sqrt{N}/(c+1) \rfloor$. When $c>(1/2)\log N$, some of the CSE's must be between stage 1 and stage $(1/2)\log N$. Therefore, at least two elements from $I_{(1/2)\log N}$ are needed to create the crosstalk blocking—not better than the case when $c=(1/2)\log N$. Thus, the total number of planes for nonblocking remains the same as the case $c=(1/2)\log N$.

Now we investigate the case when $\log N$ is odd. Same as when $\log N$ is even, we again observe that the connections originating from I_1 through $I_{(\log N\pm 1)/2}$ and destined for O_1 through $O_{(\log N\pm 1)/2}$ can block the tagged path regardless of the type of blocking. The difference we need to consider are connections from $I_{(\log N\pm 1)/2}$ to $O_{(\log N\pm 1)/2}$ since they can cause crosstalk-blocking. When $1 \le c \le (1/2)(\log N - 1)$, any path from $I_{(\log N\pm 1)/2}$ to $O_{(\log N\pm 1)/2}$ with c CSE's can cause crosstalk-blocking. This requires that the c CSE's themselves originated from $I_{(\log N\pm 1)/2}$ or destined for $O_{(\log N\pm 1)/2}$. Since there are $2^{(\log N-1)/2}(\log N \pm 1)/2$ elements (or $\sqrt{2N}/2$) in each set, the total number of additional planes is $\lfloor (2\cdot(\sqrt{2N}/2))/c+2 \rfloor = \lfloor \sqrt{2N}/c+2 \rfloor$. The cases when $(1/2)(\log N-1)<c<\log N$ can be done in exactly the same way. The result will be $y = \lfloor \sqrt{2N}/2(c+2) \rfloor$. QED.

The analysis in details can be found in the appendix proved by Vaez and Lea (2000) [11]

3.2 Conservative Routing Strategy for Upper-bound on Blocking Probability in VSOB Networks

In order to implement the possible maximum blocking probability in the VSOB network, we named our routing strategy as conservative router[4]. Before discussion, we define the workload r as the occupancy probability of an input/output port. For a group of given connection requests which according to the workload r, we firstly count the connection requests which will cause link-blocking on tagged path (the first input/output pair). The remained problem is to find the possible maximum number of connection requests which will cause crosstalk-blocking and block the banyan plane under certain degree of crosstalk. For example, when c=2, we count the number of connection requests which cause link-blocking on the tagged path as m_{lb}, the number of connection requests which will cause crosstalk-blocking as m_c. To be sure that every three connection requests in set m_c should be in two individual planes. In another words, two of the three connection requests will block one plane in the VSOB network and the remained connections request could share one plane with the tagged path. The number of blocked planes, we record it as m_{cb}. Then, we can get the possible maximum planes (m_{lb}+ m_{cb}) blocked by the generated connection requests pattern. The blocking probability is estimated by the ratio of number of blocked planes to the total number of available planes in the VSOB network, same the blocking probability discussed in [4, 5].

The following flowchart Fig.3 shows the example of c=2, how the conservative routing control strategy works.

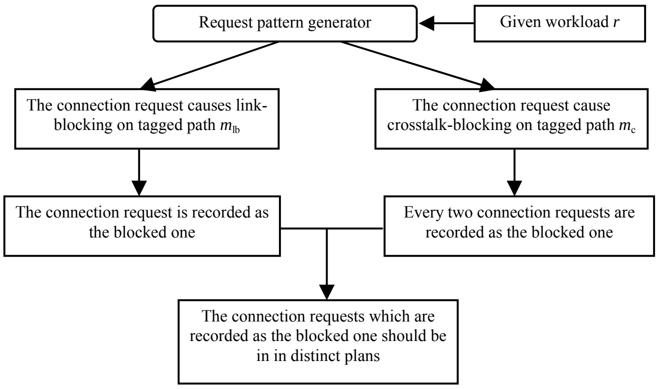

Fig.3 Conservative routing strategy

4. Implementation on Upper Bound of Blocking Probability

An experimental simulation based on a network simulator has been performed to validate our ideas on blocking probabilities of VSOB networks under various degree of crosstalk (c=0,1,2,3). Our network simulator randomly generates a set of connection request patterns for a VSOB network based on the occupancy probability r of an input/output port. To implement our upper bound on blocking probability, we use the designed conservative routing strategy to route the connection requests of a connection pattern through the VSOB network. In the "conservative" routing strategy, each connection requests group block the tagged path will be in a distinct plan. A connection pattern is recorded as a blocked connection pattern if it can block all the planes of a VSOB network under the "conservative" routing strategy. The upper bound on blocking probability is then estimated by the ratio of number of blocked connection patterns to the total number of connection patterns generated.

Fig.5 illustrates the minimum number of planes estimated by our implementation for negligible blocking probability (denoted by *BP* hereafter) under different degree of crosstalk constraint. For comparison, we also show in Fig.4 the minimum number of planes given by the condition of a strictly nonblocking VSOB network (c=0) implemented by our simulator.

The results in Fig.4 indicate that, for larger size networks, the hardware costs given by nonblocking condition are

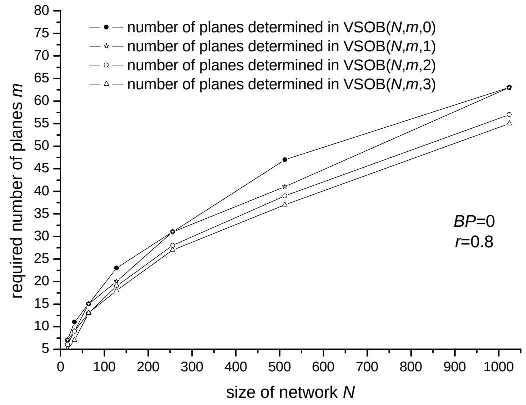

Fig.4 Minimum number of planes for strictly nonblocking VSOB networks

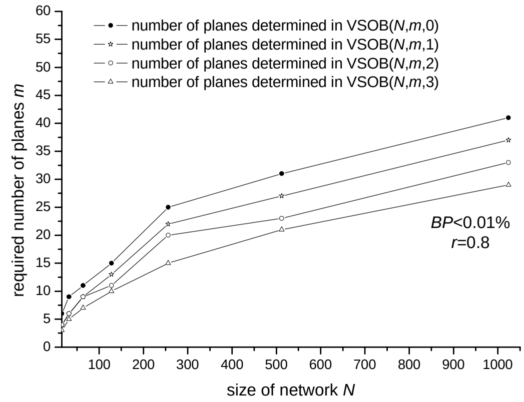

Fig.5 Minimum number of planes for negligible blocking VSOB networks

considerably higher than that given by the upper bound even for a high requirement of blocking probability. For a switching network with N=512, the minimum number of planes given by the nonblocking condition is 47, 41, 39, 37 for c=0, 1, 2 and 3 respectively, while the minimum number of planes given by the implementation are 31, 27, 23, 21 for VSOB with BP <0.01%, so the (47-31)/47≅34%, (41-27)/41≅34%, (39-23)/39≅41% and (37-21)/37≅43% of the hardware can be reduced respectively while a very low blocking probability is guaranteed (BP<0.01%). It is interesting to note that by increasing the degree of crosstalk, the hardware cost will be more reduced when the same blocking probability constraint in the VSOB network. It is an efficient tool to find the relationship among hardware cost, blocking probability and degree of crosstalk.

We have also examined two network configurations, N=512 and N=1024, for upper bound implementation. For each configuration and r=0.8, the blocking probabilities were generated under c=0, 1, 2, 3. The corresponding results are summarized in Table 1 and Table 2. The comparison results in both Table 1 and Table 2 show clearly that the blocking probability is in sense of crosstalk. And we should note that our implemented upper bound follows closely with the conditions of strictly nonblocking VSOB networks as shown in lemma 1. For N=512, the upper-bound blocking probability goes to zero at m=47 when c=0; goes to zero at m=41 when c=1; goes to zero at m=39 when c=2 and goes to zero at m=37 when c=3. For N=1024, the upper-bound bloc-

Table 1: Blocking probability Versus Degree of crosstalk in 512×512 VSOB network

m	BP (r=0.8)			
	c=0	c=1	c=2	c=3
1	0.99997	0.91949	0.86818	0.83512
2	0.99934	0.79915	0.79197	0.76228
3	0.99356	0.68799	0.67316	0.68537
4	0.96379	0.563	0.551	0.46531
5	0.86962	0.46889	0.41892	0.34973
6	0.67812	0.37765	0.30593	0.26184
7	0.42256	0.22063	0.12063	0.11597
8	0.19744	0.09251	0.00747	4E-5
9	0.06632	0.00283	0.00184	9E-7
10	0.01565	4.9E-4	1.5E-4	1E-10
11	0.00257	2E-5	1.7E-7	1E-10
12	2E-7	1E-10	1E-10	1E-10
13	1E-10	1E-10	1E-10	1E-10
14	1E-10	1E-10	1E-10	1E-10
15	1E-10	1E-10	1E-10	1E-10

Table 2: Blocking probability Versus Degree of crosstalk in 1024×1024 VSOB network

m	BP (r=0.8)			
	c=0	c=1	c=2	c=3
1	0.99999	0.96511	0.96372	0.92987
2	0.99984	0.92954	0.91372	0.89897
3	0.99788	0.89536	0.87297	0.81562
4	0.98396	0.81182	0.79173	0.77395
5	0.92279	0.77886	0.72214	0.68533
6	0.75384	0.63905	0.59371	0.45186
7	0.66716	0.54018	0.48254	0.30784
8	0.38552	0.27884	0.11937	0.09598
9	0.13964	0.09954	0.01346	4.95E-4
10	0.02951	0.00384	3.1E-4	2.1E-8
11	0.01103	7.4E-5	6.9E-6	1E-10
12	3E-6	2E-7	8E-8	1E-10
13	3E-8	2E-10	1E-10	1E-10

14	1E-10	1E-10	1E-10	1E-10
15	1E-10	1E-10	1E-10	1E-10

king probability goes to zero at m=63 when c=0. The results in Table 1 and 2 also indicate clearly that it is possible for us to dramatically reduce the hardware cost (number of planes) by tolerating a predictable and negligible blocking probability by increasing the degree of crosstalk. So our bound can initiates a graceful tradeoff between hardware cost and overall blocking probability.

5. Conclusions

In this paper, we have implemented the upper bound on blocking probability of VSOB networks under certain degree of crosstalk constraint. Our implementation describes accurately the overall blocking behaviors of VSOB networks as confirmed by simulation on a network simulator. The numerical results in section IV can provide network developers with a guidance of quantitatively determining the effects of various small degrees of crosstalk and reduction in number of planes on the overall blocking behaviors of VSOB networks. The numerical results can also show how the crosstalk adds a new dimension on the VSOB networks and the effecting of crosstalk on hardware cost and blocking probability. We expect that the results in this paper will be helpful for deriving the upper bound on blocking probabilities of VSOB networks under common degree of crosstalk constraint in both the implementation and theory.

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