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An ECO Algorithm for Resolving OPC and Crosstalk Violations

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Abstract

In the deep submicron manufacturing (DSM) era, lithography/yield and noise are critical issues to be considered. Optical Proximity Correction (OPC) is becoming a key compensate technique for the light diffraction effect in lithography. Both OPC effect and the capacitive crosstalk on some wire segments can only be analyzed post routing in late design stage or post-silicon stepping design change. ECO (Engineering Change Orders) is used in late design stage to fix violations that exceed the given OPC and crosstalk thresholds derived from analysis. These violations must be corrected in order to guarantee performance and yield. In this paper, we propose the first ECO routing algorithm which eliminates both OPC and crosstalk violations for wires. At the same time, the ECO routing obeys the given constraints so as to keep the new routing solution close to the existing one to preserve design timing and layout convergence.

1. Introduction

As the technology scales down into the deep submicron, the sub-wavelength lithography introduces a huge burden in the manufacturing process since the diffraction of light physically limits the critical dimension (CD).

Optical Proximity Correction (OPC) is proved to be an effective method to compensate the light diffraction effect as a post layout process. However, the post design layout polygon manipulation process is time-consuming and the results are still limited by the original layout. So it is preferred to fix the OPC violations in the design stage.

Both light diffraction and crosstalk are local effects (diffraction usually can be ignored after 3 wave-length and crosstalk decreases quickly after short distance); and, the analysis [1, 8] can only be derived post routing where most design are done and timing are converged. It is also common to get more accurate models and analysis on both yield and noise after silicon is manufactured and fix them during design stepping.

On the other hand, ECO changes are almost inevitable in late stages of a design process, usually for fixing timing or layout problems. Instead of re-doing the whole design process, designers prefer to modify the existing solution incrementally and keep the design as close as possible to the existing one to preserve already converged timing and layout while fixing issues identified by late analysis or manufacture feedback to increase yield and noise margin. Based on the post analysis [1, 2] , the lithography simulation of OPC effects on some segments can be identified large enough to affect yield, reliability or timing (i.e., risky area for possible large difference from drawn layout in silicon due to diffraction) in existing design. Similarly, the total capacitive crosstalk on some signal wire segments can be identified to be larger than their allowable bounds after post-layout timing/noise analysis. Therefore, a clean routing solution without OPC and crosstalk violations is needed. Meanwhile, the new design should obey certain constraints which help to keep the new design close to the original one.

In this paper, we present the first ECO routing algorithm OCVE (OPC Crosstalk Violation Elimination) which targets to resolve both OPC and crosstalk violations.

In previous works, [2] presented an OPC-friendly maze routing. Several papers [3, 4, 6, 9, 10] addressed the global/detail routing with the crosstalk constraint. However, ECO problems require keeping the modified design as close as possible to the existing one. So more constraints are set in order to minimize the disturbance on the existing design. Recently, [8] proposed an ECO algorithm to remove crosstalk violations. But no consideration was taken for OPC effects.

In this paper, we first give the definition of OCVE (OPC Crosstalk Violation Elimination) problem in section 2. Then in section 3, we briefly review the OPC model, the crosstalk model and FP-range which helps to avoid overlaps on other neighbor layers. In section 4, we present the OCVE algorithm to resolve OPC and crosstalk violations. Finally, we show the experimental results in section 5 and conclude the paper in section 6.

2. Problem Formulation

Suppose a routing solution S has N signal wire segments on layer L. Without loss of generality, we assume the metal layer L is used for horizontal tracks, and the layers below and above L, which are $\hat{L}$ and $\tilde{L}$, respectively, are used for vertical tracks. Any changes on L may lead to changes on other layers. However, the changes should not propagate to all layers. Therefore, we confine the changes to L, $\hat{L}$ and $\tilde{L}$, and treat all connections to these three layers from other layers as fixed pins.

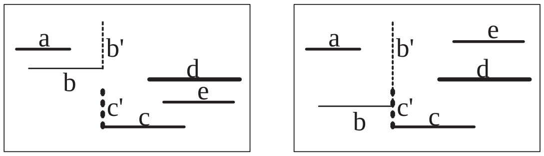
For each wire segment, it has two thresholds p and c. p is the OPC threshold, i.e., the total OPC effect on the segment should not exceed this bound. c is called crosstalk threshold, i.e., the total capacitive crosstalk on the segment cannot be larger this bound.

A horizontal segment can be represented as $(x_1, x_2, y, w, p, c, d)$ where (x_1, y) and (x_2, y) are the end point coordinates of the center line $(x_1 < x_2)$, and w is the half-width of the segment, p is the OPC threshold, c is the crosstalk threshold, and d is the allowable deviation bound, i.e., when the segment moves up/down, its new position $(x_1, x_2, \bar{y}, w, p, c, d)$ should satisfy $|\bar{y} - y| \leq d$. Similarly, a vertical segment can be represented as $(y_1, y_2, x, w, p, c, d)$. Sometimes, we can simplify the representation. For example, a horizontal segment can be represented by (x_1, x_2, y) if we do not care other factors.

Since the OPC or crosstalk effects on some segments in S exceed the given bounds, the target is to modify the existing routing solution S so that the new routing solution $\bar{S}$ is a clean routing solution which satisfies the following constraints:

1. Horizontal signal wire segments on L can only move up/down, i.e., the x-coordinates of the two end points of the segment keep unchanged.
2. The relative positions of any two segments on the same layer should not be changed. This property is called "order consistency".
3. The difference between the new position of a wire segment and its old location should not exceed its allowable deviation bound d.
4. The total OPC effect on a wire segment should not exceed its OPC threshold p.
5. The total crosstalk on a wire segment should not exceed its capacitive crosstalk threshold c.

The first three constraints are set to keep the topology of the new design close to the original one. Once a signal wire segment on layer L is moved, it may also cause changes on the neighbor layers $\hat{L}$ and $\tilde{L}$. Figure 1 illustrates an example. (a) shows an OCVE problem. The crosstalk on b is larger than its given bound, while the OPC effect on e is greater than its OPC threshold. In Figure 1 (b), segment b is moved down to reduce the crosstalk between a and b. But b' and c' on layer $\hat{L}$ overlap. Also the changes on layer L should obey the "order consistency". In Figure 1 (b), e is moved above d to reduce the OPC effect on e, but this disturbs the original wire ordering.



(a) (b)

Figure 1: (a) A routing solution on L. The crosstalk on b is larger than its given bound, while the OPC effect on e is greater than its OPC threshold. (b) Segment b is moved down to reduce the crosstalk between a and b. But b' and c' on layer $\hat{L}$ overlap. e is moved above d to reduce the OPC effect on e, but this doesn't obey "order consistency".

3. Preliminaries

3.1 OPC Model

In this paper, we use the same OPC model as the one in [2]. Fig. 2 is a simple optical system in the microlithography. The numerical aperture (NA) is defined as $NA = \sin\alpha$. It represents the quality of the lenses in the optical system. The smallest representable size in the optical system is proportional to $\frac{\lambda}{NA}$.

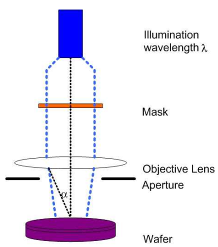


Figure 2: A simple optical system.

Let $f(r)$, where r is a two dimensional vector representing any position on a plane, be the mask for a certain layer of a layout. The $f(r)$ has a binary output: zero means the light is blocked, and one allows the light to go through the mask. The intensity of the output image $I(r)$ for an optical system with the amplitude-impulse-response $h(r)$ can be calculated by the following three models:

coherent illumination: $I(r) = |f(r) * h(r)|^2$

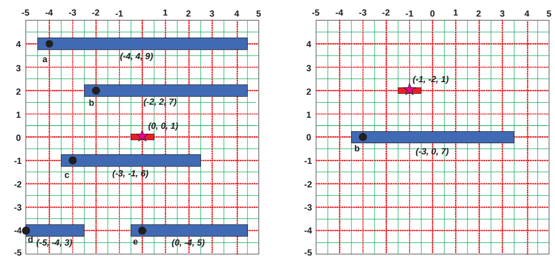
incoherent illumination: $I(r) = f(r)^2 * |h(r)|^2$

partially illumination: $I(r) = \sum_{i=1}^{n} \beta_i |f(r) * h_i(r)|^2$

where β_i is the scale factor. Partially coherent systems can be approximated as the sum of coherent systems.

The ideal amplitude-impulse-response function $h(r)$ is a *sinc*-like function. If the wavelength of the optical system is λ, with numerical aperture NA, the width W of the main lobes of $h(r)$ would be $W = \frac{\lambda}{NA}$. The width of the side lobe would be $\frac{\lambda}{2 \cdot NA}$. Since the amplitude decays sharply beyond the first side lobe, we can think of the closest edges of the two adjacent patterns as the first order factor in the cost function. The rest of the edges on the patterns are second order, third order, and so on. If the edge falls beyond the first side lobe, its effects would be ignored. The design rules basically capture the first order factor from the geometry. However, since the CD is smaller than the wavelength nowadays, the second order or the third order edge would fall into the effective region and cannot be ignored.

The optical interference is limited within a region of several wavelengths. To calculate the interference on a certain edge from other routed patterns on the routing grid graph, only patterns within the effective region centered at the edge are necessary, as shown in Fig. 3 (a). Note that the coordinates represent the center of each wire segment. All patterns within the effective region are marked with coordinates of the left-most edge and the lengths of the patterns. The optical interference on the wire segment is the summation of the interference from all effective patterns. As long as the relative positions stay the same, all of the optical effects would be equivalent. For example, to obtain the interference from the pattern b shown in Fig. 3 (a), the pattern b in Fig. 3 (a) are shifted and mirrored, as shown in the figures from Fig. 3 (b). Therefore, the optical interference can be simulated for all lengths of patterns centered at the origin. The result is kept in an OPC loop-up table. Note that the routing grid size if different from the optical simulation grid size. The mean value within the grid size is recorded in the table. Furthermore, if the optical system does not have the symmetric property in certain axis, the mirror operation would not be allowed and the size of table would be doubled.



(a) (b)

Figure 3: (a) Five patterns are within the effective window of the edge $(0,0)$. Each effective pattern is denoted by the left most edge coordinated and its length. (b) Pattern b is shifted and centered to the horizontal axis, while the evaluated edge could be mirrored to the upper part of the effective window if the optical system is symmetric on the horizontal axis.

The optical interferences from all effective patterns are looked up from the table. The sum of the values represents the total effect of the interferences.

3.2 Crosstalk Model

In general, each segment has coupling effect to all other segments. However, the coupling capacitance decreases drastically if the segment is out of the neighborhood of the other segment [5, 9, 10]. Therefore, we only consider the capacitive crosstalk between two neighboring parallel wires and suppose the neighborhood distance is D. Then the capacitive crosstalk between two segments can be expressed as the following formula:

$$c = \begin{cases} \alpha \cdot \frac{l}{t^\beta} & t \le D \\ 0 & t > D \end{cases}$$

where α is the coupling parameter, β is an experimentally estimated constant [5], l is the coupling length, and t is the distance between two segments.

3.3 FP-Range

To avoid introducing vertical overlaps on the neighbor layers $\hat{L}$ and $\tilde{L}$, we specify FP-Range for each wire segment [8].

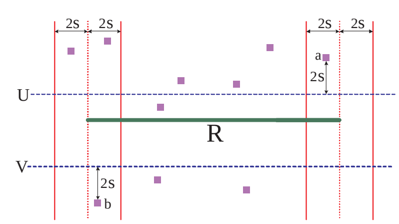


Figure 4: FP-Range illustration. Tiny squares are fixed pins.

FP-range is defined as follows. Suppose the wire separation requirement is $2s$, and W and H are the width and height of the routing region, respectively. A horizontal wire segment $R = (x_1, x_2, y_r)$ on L has two end points $r_1 = (x_1, y_r)$ and $r_2 = (x_2, y_r)$. Suppose the two end points are connected to layer L' and L'', respectively. L' (L'') can be either $\hat{L}$ or $\tilde{L}$. Then calculate two pin sets $\tilde{P}$ and $\tilde{Q}$. Let

$\tilde{P}$ be the set of fixed pins on L and L' whose x-coordinates fall in $(x_1 - 2s, x_1 + 2s)$, and $\tilde{Q}$ be the set of fixed pins on L and L'' whose x-coordinates fall in $(x_2 - 2s, x_2 + 2s)$. Let $U = min\{\{y - 2s | y \in \tilde{P} \cup \tilde{Q} \wedge y \geq y_r\} \bigcup \{H - 2s\}\}$ and $V = max\{\{y + 2s | y \in \tilde{P} \cup \tilde{Q} \wedge y \leq y_r\} \bigcup \{2s\}\}$. The range $[V,U]$ is called "FP-Range". Figure 4 shows the FP-Range of a horizontal segment R. Pin a is the closet pin above R and pin b is the closet pin below R. In this example, the FP-Range of R is $[y_b + 2s, y_a - 2s]$ where y_a and y_b are y-coordinates of pin a and b respectively.

Then we have the following theorem. The proof is similar to [7] and it is omitted here.

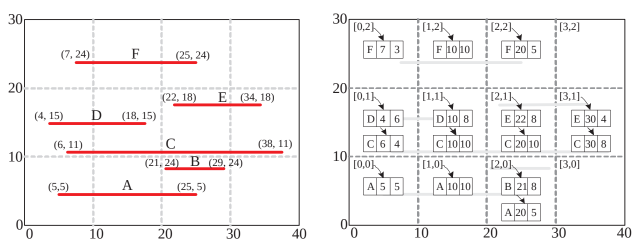
Theorem 1. *If all horizontal segments on layer L move up/down within their FP-Ranges $[V,U]$ and satisfy horizontal wire separation requirement and order consistency, the new routing solution has no vertical wire separation violations.*

4. OCVE Algorithm

To solve the OCVE problems, we need to handle two kinds of violations, i.e., OPC violations and crosstalk violations. OPC effects are mainly decided by OPC effective region, while crosstalk is determined by neighbor segments. Therefore, we adopt two different data structure, loop-up table and graph, to assist OPC and crosstalk calculation during the wire movement.

4.1 Segment Loop-up Table

Given a routing region (W,H), claim a two-dimension array MAP $[\lfloor W/R_w \rfloor, \lfloor H/R_h \rfloor]$, where R_w and R_h are two positive numbers set by users. The elements of MAP are a set of segments as well as the wire segment length. A segment P (x_1, x_2, y) is recorded in MAP $[i, \lfloor y/R_h \rfloor]$, $i = \lfloor x_1/R_w \rfloor ... \lfloor x_2/R_w \rfloor$. In MAP $[i, \lfloor y/R_h \rfloor]$, the segment length related to P is assigned as $\min(x2, (i+1) * R_w) - \max(x1, i * R_w)$. Figure 5 shows an example. Figure 5 (a) gives a routing solution with 6 horizontal wire segments. Figure 5 (b) is the segment look-up table MAP. Each item in the grid has three parts: the segment id, the starting point of the wire segment in the grid cell as well as its length. For example, segment A is recorded in MAP$[0,0]$, MAP$[1,0]$ and MAP$[2,0]$. And the lengths in these three cells are 5, 10 and 5, respectively.



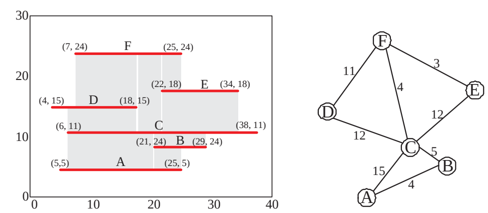
(a) (b)

Figure 5: (a) A routing solution with 6 horizontal wire segments on L. (b) The corresponding segment loop-up table. $R_w = R_h = 10$. For each item in a grid cell, the first part is the segment id, and the next two are the starting point and the wire length of the wire segment length in the grid cell.

Once we set up this loop-up table, we can easily find all effective patterns for a selected wire segment. For example, the segment D in MAP$[1,1]$ is $(10,18,15)$. Suppose the OPC effective region for this wire segment covers a region whose left bottom corner and right upper corner are $(2,11)$ and $(26,19)$, respectively. Then we only need to check MAP$[0,1]$, MAP$[1,1]$ and MAP$[2,1]$ to find the segments in the effective region. From the OPC table which is pre-build according to the OPC model, we can get the OPC effects on D and the segments in the effective region as well.

4.2 Segment Neighboring Graph

The crosstalk coupling effect occurs between two neighbor segments. Since the horizontal wire segments on layer L can move only up/down, and the ordering of these wire segments cannot be changed, the wire neighboring relationship won't be changed either. Therefore, we can pre-check wires to see if two wire segments are adjacent to each other, and represent the wire neighboring relationship by a plannar graph.



(a) (b)

Figure 6: (a) A routing solution on L. The grey area show the adjacent overlap between two wire segments. (b) The corresponding segment neighboring graph. Each wire segment is represented by a node. For any two nodes, if they are adjacent to each other, an edge is added. A number is associated to an edge which is the coupling length of the two segments.

Each wire segment is represented by a node. For any two horizontal wire segments $A = (x_1^a, x_2^a, y^a)$ and $B = (x_1^b, x_2^b, y^b)$, $(y^a < y^b)$, let $x_l = \max(x_1^a, x_1^b)$ and $x_r = \min(x_2^a, x_2^b)$. If $x_l < x_r$, then the two wire segments have overlap along x-dimension. Furthermore, if there is a rectangle region whose left bottom corner is (x', y^a) and right upper corner is (x'', y^b) $(x_l \leq x', x'' \leq x_r)$, and there is no other wire segments fall in this region, the two wire segments are neighbor wires, and one edge is added between the two segments. Also the total coupling length which will be used for crosstalk calculation is assigned to the edge. Figure 6 shows an example. Figure 6 (a) is a routing design on layer L. The gray boxes indicate the adjacency between two wire segments, and the width of a gray box is the capacitive coupling length of the two segments. Figure 6 (b) is the segment neighboring graph. Each wire segment is represented by a node. If any two segments have the coupling effect, an edge is added and the coupling length is assgned to the edge. It's easy to see that the segment neighboring graph is a planar graph. The number of nodes is $|N|$, and the number of edges is at most $3|N| - 6$, where $|N|$ is the total number of segments.

4.3 OCVE Algorithm

To solve the OCVE problem, we also draw on the segment neighboring graph G to maintain the order consistency. For convenience, for any two segments A and B in G, if A is above B and there is a path from A to B, we say A is B's parent, and B is A's child.

First initialize all nodes in the segment neighboring graph as "unprocessed". Each time, select the nodes which have no parent nodes which are "unprocessed", and move them to their highest available positions. These positions are their new locations. Then mark these nodes as "processed". Repeat this process until no nodes are "unprocessed".

For each segment, its available position is decided by its FP-Range, allowable deviation bound, the positions of its parents, the OPC threshold and the crosstalk threshold. Let the wire separation requirement be $2s$. Suppose segment $A = (x_1, x_2, y, w, p, c, d)$ has an FP-range $[V,U]$. Also A records a value $Ubound$. Initially, $Ubound = min\{y_p - 2s - w_p | y_p$ is the y-coordinate of an A's parent node and w_p is its half width $\}$. Then if A moves in the range $[0, Ubound - w]$, the order consistency is guaranteed. Let $[\bar{V}, \bar{U}] = [V,U] \cap [y-d, y+d] \cap [0, Ubound - w]$. Check tracks t starting from $\bar{U}$. If no OPC and crosstalk violations are introduced to A's parents and itself when A is put at track t, and t is assigned as A's new position. Otherwise, check the next track below t. To calculate OPC or crosstalk, since the positions of the children segments of A as well as some other segments are not decided, it's hard to estimate their effect. But for "processed" segments, their positions are fixed. Therefore, we only consider OPC and coupling effects between "processed" segments and A. The target is that the new position will not cause OPC or crosstalk violations to a "processed" segment as well as to the segment A itself. To calculate OPC, we

Table 1: Test Results of OCVE Problem

File	NetH1	NetV1	WireH1	WireV1
ECO Region Area(um^2)	464.66x343.28	332.99x495.32	1090.67x490.56	483.42x1099.28
Signal Segments	1563	2270	1483	1408
OPC Violation Segments	457	607	387	382
Crosstalk Violation Segments	403	433	364	381
Allowable Deviation	2%	2%	2%	1%
Test Results				
OPC Violation Segments	0	0	0	0
Crosstalk Violation Segments	0	0	0	0
Running Time (s)	228	240	375	216

can efficiently identify the segments in A's effective region according to the segment loop-up table. For each pair of segments in the effective region, the OPC interference value can be obtained by the pre-established OPC look-up table. For crosstalk, we can find the direct parents of A in the segment neighboring graph. The edge value is the coupling length of the two segments. Then we can apply the crosstalk model directly to get the capacitive coupling value. This process is repeated until a feasible position is found or the track goes beyond $\bar{V}$. The latter case means no feasible solution is found. Once the position of A is decided, the OPC and crosstalk bounds of A and A's parents have to be adjusted accordingly, i.e., subtract the OPC effect and crosstalk between A and its parents from the corresponding bounds of A and its parents.

OCVE algorithm can be summarized as follows. S_h is the set of horizontal signal wire segments, R is the set of fixed pins, P, C, and D record the OPC threshold, crosstalk threshold, and the allowable derivation bound, respectively. For each node q, its $Ubound$ is denoted as $q.Ubound$, its FP-range is $[q.V, q.U]$ and its allowable deviation bound is $[-q.d, q.d]$.

Algorithm OCVE(S_h, R, P, C, D)
1. Read in OPC Look-Up Table;
2. Construct Segment Look-Up Table T;
3. Construct Segment Neighboring Graph G;
4. For any node n
5. $[n.Lbound, n.Ubound]$ = $[n.V, n.U] \cap [n.y - n.d, n.y + n.d]$;
6. $n.status$ = "unprocessed";
7. Push nodes without "unprocessed" parents into List L;
8.
9. While $(L \neq \phi)$ do
10. Remove a node q from L;
11. new_pos = $q.Ubound$;
12. While ($new\_pos \geq q.Lbound$) do
13. If ((q and q's parents have no OPC violations)
14. && (q and q's parents have no crosstalk violations))
15. then $q.pos$ = new_pos;
16. update q and q's parents OPC bounds;
17. update q and q's parents crosstalk bounds;
18. update q's children's $Ubound$;
19. $q.status$ = "processed";
20. break;
21. else new_pos--;
22. End_While;
23. If no position is found, return "No Solution";
24. Push the nodes without "unprocessed" parents into L;
25. End_While

The changes on layer L may lead to the changes on $\hat{L}$ and $\tilde{L}$. The deviation bound d is defined to constrain that one segment does not deviate too much from its original position. At the same time, it helps to prevent introducing new violations to other layers. When horizontal segments on L move up or down, the length changes of the vertical segments on $\hat{L}$ or $\tilde{L}$ is no more than $2d$ since each vertical segment connects to at most two horizontal segments on L. Then the OPC or the coupling effect introduced by length increase is also limited. Therefore, if the neighbor layers of layer L are not critical on OPC or capacitive crosstalk, by setting appropriate deviation bounds, we can avoid introducing new OPC/crosstalk violations on layer $\hat{L}$ or $\tilde{L}$. On the other hand, if the neighbor layer is sensitive to the changes, we need to check the neighbor layer as well so that after each change, no new violation is introduced. The OPC/crosstalk violation checking on other layers is the same as the checking on layer L. This step can be easily plugged after Line 14.

In this algorithm, each time we always put a horizontal segment to its highest available position. This leaves more room for other segments since once one segment is processed, its location is fixed and other segments below it cannot take the places above it. On the other hand, another goal of the algorithm is to minimize the total deviation. Therefore, we start with a zero allowable deviation bound and each time increase the bound by a certain percentage. Repeat this process until a feasible solution is found or the deviation bound exceeds the pre-defined value. For the latter case, no feasible solution is found.

5. Experimental Results

Our algorithm was implemented in C++ on PC workstation(1.8GHz) with 1.5GB memory. We tested OCVE algorithm on four test files as listed in Table 1. The optical wavelength is 193nm, and the line width and space are based on 90nm process. For all of the test circuits, the allowable deviation of each signal wire segment is bounded as 2% (1% for WireV1) of the height of the ECO region area. After applying the OCVE algorithm, we can find clean routing solutions for all four files.

6. Conclusion

In this paper, we propose the first ECO routing algorithm which eliminate both OPC and crosstalk violations for wires on one layer. At the same time, the ECO routing obeys the given constraints so as to keep the new routing solution close to the existing one. Furthermore, the OCVE algorithm can be applied layer by layer to resolve violations on all layers to a given multiple layer routing design. Experimental results demonstrate the efficiency and effectiveness of our approach.

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