DYNAMIC AND ADAPTIVE TESSELLATION OF BÉZIER SURFACES

R. Concheiro, M. Amor
University of A Coruña, A Corua, Spain

M. Bóo
University of Santiago de Compostela, Santiago de Compostela, Spain
montserrat.boo@usc.es

M. Doggett
Lund University, Lund, Sweden

Keywords: Adaptive tessellation, GPU, Bézier surfaces.

Abstract: Bézier surfaces offer powerful mechanisms to describe high quality models in computer graphics. In this paper we present a methodology for the implementation of the adaptive tessellation of Bézier models on the GPU. Tessellation is performed with variable resolution inside the patch to permit the use of meshes with a lower number of triangles but preserving a high visualization quality. Primitives are dynamically generated according to the results of local subdivision tests. The locality of the decisions assures that contiguous triangles are coherently subdivided.The resulting procedure is efficient, simple and generates the tessellation pattern of each Bézier surface dynamically. This enables tessellation of complex models to be performed in real time.

1 INTRODUCTION

Bézier representations have been widely employed as a standard way of designing complex scenes with very good quality results. In many applications involving CAD/CAM, virtual reality, animation and visualization, object models are described in terms of Bézier surfaces. The excellent mathematical and algorithmic properties (Piegl and Tiller, 1997), combined with successful industrial applications, have contributed to the popularity of this representation.

Traditionally, for the rendering process the Bézier models are tessellated on the CPU (*Central Processing Unit*) and the set of generated triangles is sent to the GPU (*Graphic Processing Unit*). The CPU-GPU bus can become a bottleneck in this approach due to the large number of triangles generated for high quality models. Nowadays, there are some approaches to perform the tessellation of the parametric models directly on the GPU. In these proposals the tessellation level is selected per patch (Guthe et al., 2005; Concheiro et al., 2010) or per set of patches (Dyken et al., 2009). Another tessellation approach is presented in (Eisenacher et al., 2009; Schwarz and Stamminger, 2009) where the tessellation is performed following a GPGPU strategy (General-Purpose Computation on GPU). In a similar way, all these proposals are adaptive at the patch level, that is, once the resolution for a patch is determined, the patch is subdivided in a uniform way (with specific modifications in the border of the patch to assure no holes or cracks between neighbor patches).

Until recently, the programmable vertex and pixel shaders found in GPUs could only operate on existing data. The scene changed a few years ago with the introduction of a new programmable unit, the geometry shader and the introduction of new tessellation stages (hull shader, tessellator and domain shader) (Ni and Castaño, 2009). Some adaptive tessellation proposals for triangles meshes exploiting geometry shader have been developed (Bóo et al., 2011; Lorenz and Döllner, 2008) and no one, as far as we know, is focused on the adaptive tessellation of parametric models at the triangle level. The scene did not change with the introduction of the new tessellator unit because it applied a fixed and semi-regular pattern also at the patch level.

Concheiro R., Amor M., Bóo M. and Doggett M..
DYNAMIC AND ADAPTIVE TESSELLATION OF BÉZIER SURFACES.
DOI: 10.5220/0003361001000105
In *Proceedings of the International Conference on Computer Graphics Theory and Applications* (GRAPP-2011), pages 100-105
ISBN: 978-989-8425-45-4

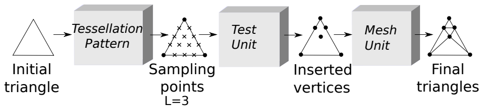


Figure 1: Scheme of the DABT algorithm.

In this paper we present a new method to adaptively tessellate Bézier surfaces on the GPU. Our Dynamic and Adaptive Bézier Tessellation (DABT) proposal permits the minimization of the number of triangles to be processed without reducing the quality of the final images. To increase the adaptive properties of previous proposals, neighbor triangles can be tessellated with a different resolution without cracks. Therefore, our method tessellates Bézier surfaces in an adaptive way, so real-time rendering of complex models can be achieved.

2 DYNAMIC AND ADAPTIVE BÉZIER TESSELLATION

In this section we present our Dynamic and Adaptive Bézier Tessellation (DABT) proposal. Our strategy performs the adaptive tessellation of the Bézier surface by computing the tessellation pattern on-the-fly without employing a set of pre-computed patterns. The objective is a freely adaptive tessellation inside each patch where the resolution and number of triangles generated can be selected as a trade off between quality and computational requirements. The methodology we propose is based on local tests, the resulting model has no cracks or holes, neither inside each patch nor between neighbor patches.

Specifically, our DABT method is based on three different key proposals: the utilization of a fixed tessellation pattern that guides the adaptive tessellation, the application of local tests and an efficient meshing procedure to reconstruct the resulting mesh once the tests are applied. Figure 1 schematically shows these three key cores of the algorithm.

2.1 Utilization of a Fixed Pattern to Guide the Adaptive Tessellation Procedure

The objective of the proposal is to exploit the large number of cores available in current GPUs. With this objective in mind the patches of the model are initially tessellated and the coarse triangles employed as input primitives for the application.

Tessellation algorithms with a recursive nature have different disadvantages. For this reason the

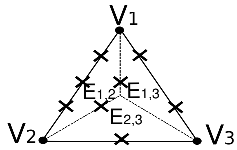


Figure 2: Example of triangle with three different resolution areas.

DABT method employs a non recursive strategy based on the utilization of a non adaptive tessellation pattern as a basis for the adaptive case. Once the tessellation level of the pattern is selected only the positions in this tessellation pattern are evaluated for conditional insertion at each position.

Figure 1 shows the tessellation patterns we employ for a level of resolution $L = 3$. The original coarse triangle is depicted with bold lines and the sampling points corresponding to the candidate vertices with a cross. The parametric coordinates (u_B, v_B) of the sampling point associated with a candidate vertex V_B that lies on the Bézier surface are computed through its barycentric coordinates with: $V_B(w_i, w_j, w_k) = w_i \times (u_1, v_1) + w_j \times (u_2, v_2 + w_k \times (u_3, v_3))$, where (u_1, v_1), (u_2, v_2) and (u_3, v_3) are the parametric coordinates of the vertices of the initial coarse triangle and (w_i, w_j, w_k) are the barycentric coordinates of the candidate vertex. The barycentric values are in the interval $[0,1]$ and verify $w_i = i \cdot \delta w$, $w_j = j \cdot \delta w$ and $w_k = k \cdot \delta w$ with $i, j, k = 0, ...L+1$ and $\delta w = \frac{1}{L+1}$.The tessellation is performed in the parametric domain, for the specific case of a bi-cubic Bézier surface the following equation is evaluated:

$$Q(u,v) = [u^3 \ u^2 \ u \ 1] \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} B_{0,0} & B_{0,1} & B_{0,2} & B_{0,3} \\ B_{1,0} & B_{1,1} & B_{1,2} & B_{1,3} \\ B_{2,0} & B_{2,1} & B_{2,2} & B_{2,3} \\ B_{3,0} & B_{3,1} & B_{3,2} & B_{3,3} \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v^3 \\ v^2 \\ v \\ 1 \end{bmatrix} \quad (1)$$

In order to enrich the adaptive tessellation possibilities, we have developed a method for the assignation of different resolution levels to neighbor triangles. With this non uniform approach, the resolution level can be dynamically selected and modified along the patch. Specifically a resolution level is selected per triangle edge so one triangle could have three resolution levels. In order to apply three levels per triangle, each one would be applied to one third of the triangle. Figure 2 shows a triangle where three different resolution levels coexist. In this example the area

$E_{1,2}$ follows a tessellation pattern $L = 3$ that means that three rows of candidate vertices have to be analyzed. Area $E_{1,3}$ is subdivided according to a tessellation pattern $L = 2$, that is, two rows of candidate vertices have to be considered. Finally, $E_{2,3}$ is tessellated with a resolution level $L = 1$.

2.2 Tests Employed to Guide the Adaptive Tessellation

The candidate vertices are conditionally inserted according to the result of specific tessellation tests (see Figure 1). We have evaluated different tests to guide the tessellation procedure. These tests measure, through the utilization of different quality thresholds, the increment of quality of the mesh if a given vertex is inserted.

2.2.1 Distance Test

This test analyzes the distance between the triangle mesh and the Bézier surface. Specifically the distance between a sampling point on the triangle mesh and the corresponding point on the Bézier surface is analyzed. If the distance is small enough, the triangle mesh is considered a good approximation of the surface so no vertex is inserted. On the contrary, if the distance is large the vertex is introduced as this will increase the quality of the final image. The test is given by:

$$distance = [|V_S - V_B| > t_{distance}]$$

where $t_{distance}$ is a quality threshold that is selected in function of the quality/timing requirements of the application, V_S is the corresponding sampling point on the coarse triangle by interpolating the position of the original vertices and V_B is the coordinates of the candidate vertex on the Bézier surfaces obtained by using Equation 1.

2.2.2 Vector Deviation Flat Test

The objective of this test is employing the curvature of the surface as a parameter to guide the tessellation procedure. With this test candidate vertices on flat areas are not considered for insertion as the quality of the surface would not be incremented. To check the curvature of the surface a simple vector deviation flat test (Espino et al., 2007) can be employed.

In order to reduce the costly computation of all candidate vertices our flatness test follows a per edge philosophy. In our proposal each candidate position associated with the coarse edges is analyzed and the decision performed is applied to all candidate positions of the same row and resolution area.Then, with this technique the curvature of the surface is estimated only for the sampling points on the edges of the coarse triangle and the result are employed in the interior of the projection. Specifically the test consists of the following steps:

1. Calculation and normalization of vectors $A = |V_1 - V_2|$, $B = |V_B - V_1|$ and $C = |V_B - V_2|$, where V_1 and V_2 are the extreme points of each edge.
2. Computation of the unsigned dot products $|BA|$ and $|CA|$
3. Comparison between the dot products and a threshold, t_{flat}. If one of them is smaller than the threshold, the new vertex is inserted:

$$flat = (|BA| < t_{flat})\ OR\ (|CA| < t_{flat})$$

2.2.3 Length Test

In geometric design applications rather than using a very high degree surface to approximate a very complex surface, it is more common to break the surface up into several simple surfaces. Specifically, the test is based on the utilization of the length of the coarse triangle edges as a measure of the curvature of the Bézier surface in the corresponding area.

Due to low degree of each Bézier surface and as the vertices of the coarse triangle mesh lie on the surface, if the coarse triangle is small then it can be considered a good approximation to the surface. Specifically, if the two vertices of one edge are close enough, the inclusion of additional vertices on that edge will not increase the quality of the final mesh.

This test works on the edge basis as it is only applied for the sampling points on the edges of the coarse triangle. In case a vertex corresponding to the the edge is inserted, the vertices on the same row are directly inserted. Note that the test is based on the analysis of the original vertices of the triangle and does not require the computation of the candidate vertices. The computational requirements of this new test are very low.

To test if a candidate vertex V_B has to be inserted in the edge with vertices V_1 and V_2 the following analysis is performed:

$$length = (|V_1 - V_S| > t_{length})\ AND\ (|V_2 - V_S| > t_{length})$$

that means that the point V_B is inserted only when the distance of the corresponding sampling point on the triangle V_S to both extreme vertices V_1 and V_2 is larger than a threshold t_{length}.

2.3 Tessellation Procedure

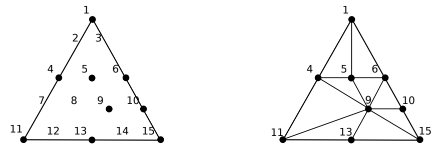
In this section, we describe the tessellation procedure employed to generate the final triangles once the inserted vertices have been determined (see Figure 1). A similar strategy was employed in (Bóo et al., 2011) for the adaptive tessellation of generic triangle meshes. This tessellation procedure is based on the classification of the inserted vertices in strips and the efficient management of the resulting list of vertices. The objective in mind is generating the triangle structure in a direct way from the irregular pattern obtained with the evaluation of the subdivision tests.

As the non adaptive tessellation patterns are characterized by a row structure, our algorithm inherits this characteristic and classifies the resulting inserted vertices in rows. A tuple of $L+2$ lists $Sv = (Sv_1, \cdots, Sv_{L+2})$ corresponding to the $L+2$ strips of vertices used. Each list includes the vertices inserted in each strip and positions of non-inserted vertices are empty. An example of adaptive tessellation is depicted in Figure 3(a) where the candidate positions are labeled with numbers and the vertices finally inserted are indicated with dots. In this case, the final tessellation pattern can be represented with the following lists: $Sv_1 = \{1\}$, $Sv_2 = \{\}$, $Sv_3 = \{4,5,6\}$, $Sv_4 = \{9,10\}$, $Sv_5 = \{11,13,15\}$

The objective is generating the final triangles by connecting the vertices in two consecutive lists. However the direct application of this technique would lead to the generation of undesired overlapping triangles. To avoid this problem, two modifications are introduced to the representation: reuse of limit vertices and incorporation of new extreme vertices. A limit vertex is a vertex located in the original edge of the triangle. If such a vertex does not exist, an extreme vertex is the first/last vertex in the list. With respect to the modification related with the limit vertices, if there is no limit vertex in a row a limit vertex from a previous row has to be included. As an example for the list of vertices corresponding to Figure 3(a) this modification implies that the Sv_4 list has to be extended as Sv_4=$\{\hat{4}, 9, 10\}$ where the reused limit vertex is indicated with a hat. The reuse of limit vertices permits the generation of triangles connecting vertices in non consecutive rows. As a consequence and in order to avoid an overlap of these large triangles with other local structures, the incorporation of new extreme vertices are required. A detailed explanation can be found in (Bóo et al., 2011).

The tessellation procedure works by processing pairs of consecutive strips of vertices. In this method the triangles are generated by joining the vertices between consecutive strips (parent-children relation) taking into account the following rules:

- Two consecutive vertices in the same strip are always connected (sibling relation).
- Two identical vertices are not considered for connection.
- A reused opening/closing limit vertex has a limited connection with the following non empty strip. Specifically, it can only be connected with a non-copied opening/closing limit vertex.
- Each non reused vertex of each strip, considered as parent, is connected with consecutive children in the following strip. The following parent is connected with another group of consecutive children. There is an overlap of one common child between two consecutive parents.



(a) (b)

Figure 3: Example of mesh reconstruction: (a) Vertices inserted. (b) Tessellation generated.

The application of these rules to each pair of extended vertex lists generates the final tessellation.

3 IMPLEMENTATION ON THE GEOMETRY SHADER

Our implementation processes bi-cubic Bézier surfaces and exploits the capabilities of the geometry shaders that permit a fully adaptive tessellation. However, the main drawback of the geometry shader is the limitation of the number of output primitives per invocation, as currently only 1024 32-bit values can be output.

The patches of the model are initially tessellated and the resulting coarse triangles are employed as input primitives for the application. To do this, the parametric domain (u,v) is partitioned in $N_u \times N_v$ cells of size $\frac{1}{N_u} \times \frac{1}{N_v}$ where two adjoining triangles are generated per cell.

Once the coarse mesh is extracted, the adaptive tessellation algorithm is applied to each coarse triangle. As was previously indicated, the tessellation procedure is based on the utilization of a non adaptive pattern to guide the tessellation. Our implementation is based on the row structure of the tessellation pattern so some modifications had to be performed to permit the processing of three resolution areas per triangle. A unified resolution is selected and employed. For a system with resolution levels L$=(0,\cdots,L_{max})$, the unified resolution level corresponds with the least common multiple of $(0,\cdots,L_{max}+1)$

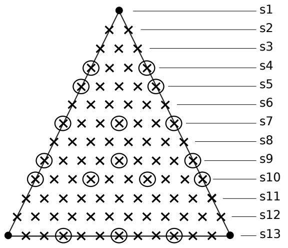


Figure 4: Unified resolution $L_{unified}$=11 for a system with L=0,1,2,3.

(a) (b) (c)

Figure 5: Models employed: (a) *Teacup*, (b) *Teapot* and (c) *Elephant*.

minus 1. As an example let us consider a system with resolutions L=$(0,1,2,3)$, in this case the unified resolution level is $L_{unified} = 11$. The barycentric weights employed for the candidate vertices for each resolution are:$w^1 = \left\{\frac{1}{2}\right\}$ $w^2 = \left\{\frac{1}{3}, \frac{2}{3}\right\}$ $w^3 = \left\{\frac{1}{4}, \frac{1}{2}, \frac{3}{4}\right\}$ being w^L the weights employed for level L. The unified system of weights is:

$$w^{11} = \left\{\frac{1}{12}, \frac{1}{6}, \frac{1}{4}, \frac{1}{3}, \frac{5}{12}, \frac{1}{2}, \frac{7}{12}, \frac{2}{3}, \frac{3}{4}, \frac{5}{6}, \frac{11}{12}\right\}$$

where $w_0^1 = w_1^3 = w_5^{12}$, $w_0^2 = w_3^{12}$, $w_1^2 = w_7^{12}$, $w_0^3 = w_2^{12}$ and $w_2^3 = w_8^{12}$. As result, a unified system of weights and rows can be employed for any resolution level. Figure 4 shows the tessellation pattern for $L_{unified} = 11$. In fact, the test unit processes only the points associated with the resolution level selected. In the figure the points corresponding to L=1 (lines s7 and s13), L=2 (lines s5, s9 and s13) and L=3 (lines s4, s7, s10 and s13) are indicated with circles.

4 RESULTS

In this section we present the results of the evaluation of our proposal in terms of the quality of the final image and frames per second (fps). We have evaluated our proposal on an Intel Core 2 2.4 GHz with 2 GB of RAM and an ATI Radeon 5870.

The models employed in the tests presented in this section are shown in Figure 5: *Teacup* in Figure 5 (a), *Teapot* in Figure 5 (b) and *Elephant* in Figure 5 (c). The scenes we have employed for our tests contain replicated and scaled versions of these models.

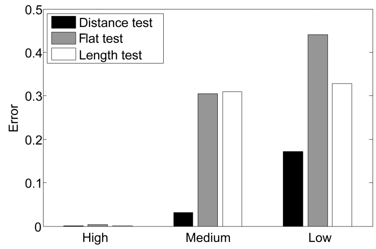


Figure 6: Error obtained with the *teacup* model for $L_{max} = 3$ and three different quality levels.

Table 1: Number of triangles generated with the different tests presented and $L_{max} = 3$.

		High Quality		
Scene\Test	# surfaces	Distance test	Flat test	Length test
Teacups	260 (10)	72.96 k	70.94 k	71.22 k
Teapots	960 (30)	267.63 k	217.24 k	266.28 k
Elephants	8110 (10)	2034.082 k	1918.933 k	2266.391 k
		Medium Quality		
Scene\Test	# surfaces	Distance test	Flat test	Length test
Teacups	260 (10)	57.49 k	57.69 k	43.15 k
Teapots	960 (30)	257.9 k	195.34 k	208.10 k
Elephants	8110 (10)	1986.02 k	1635.84 k	1781.87 k
		Low Quality		
Scene\Test	# surfaces	Distance test	Flat test	Length test
Teacups	260 (10)	15.1 k	14.49 k	15.44 k
Teapots	960 (30)	135.79 k	126.40 k	142.83 k
Elephants	8110 (10)	742.64 k	497.44 k	559.94 k

Table 1 summarizes the results obtained in terms of number of primitives. For the tests summarized in this table, $L_{max} = 3$ and three quality sets of thresholds were employed: High, Medium and Low.The second column includes the number of Bézier surfaces per scene and the number of models replicated. The third, fourth and fifth columns include the average number of generated triangles with each test presented in Section 2.2.

The tests we have performed indicate that the tessellation method produces high quality meshes with no visual artifacts. Additionally the multiresolution method employed and the utilization of multiple resolution areas per triangle have produced the expected good results. Figure 6 shows the mesh errors for a resulting scene (*teacup*), with a resolution level $L_{max} = 3$ for three different quality levels. As it can be observed and as expected the best results are obtained with the Distance test. This is due to the fact that it is the unique test performed per candidate position instead of per edge and, as a result, higher quality is obtained. Very close results are obtained with the Length test while worse results are obtained with the Flat test. Both tests are performed per edge and the results indicate that for low degree surfaces the Length test gives a good estimation of the surface curvature.

The main objective of the proposal is the real-time rendering of complex models without reducing the quality of the final image. With the objective of testing the timing requirements of the application we have analyzed a walk-through animation with the same movement of the camera for all tests. The final images have a screen resolution of 1280×1024 pixels. Figure 7 shows the results in fps using a resolution level $L_{max} = 3$ for a high quality threshold. The results indicate very good performances in terms of fps, allowing real-time adaptive tessellation, even for a high number of triangles. For example, for the Length Test 284.94 K triangles were rendered at 148.97 fps. Using this card and for a large number of triangles the Distance test has similar timing requirements than the other proposals. This is due to the exploitation of VLIW with the utilization of short vector data types (like $float4$) and vector computations.

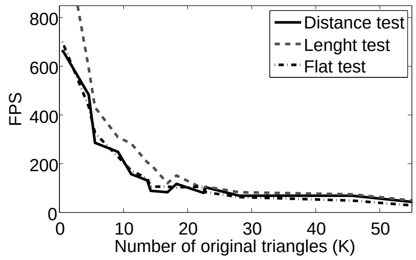


Figure 7: FPS with tessellation level $L_{max} = 3$ for a high quality threshold.

5 CONCLUSIONS

In this paper we present a new method, Dynamic and Adaptive Bézier Tessellation (DABT), for the real time adaptive tessellation of Bézier surfaces on the GPU. The method is based on the generation of an initial coarse triangle mesh that approximates the Bézier surface and the adaptive tessellation of each resulting triangle in the GPU. The methodology employed permits applying multiple resolutions to the same Bézier surface. This means that neighbor triangles can be processed with different resolutions and no visual artifacts are visible.

The proposal is based on three main strategies: the utilization of a fixed tessellation pattern to guide the procedure, the utilization of local tests for the adaptive tessellation decisions and an efficient meshing procedure to reconstruct the resulting meshes. With respect to the tests employed, we have included in this work three tests that analyze different surface features to guide the tessellation.

To test our algorithm and to evaluate the capabilities of current GPUs we have implemented our DABT algorithm by exploiting the geometry shader unit. The good results obtained in terms of quality and frames per second, makes our proposal an interesting candidate for its real hardware implementation on future GPUs.

ACKNOWLEDGEMENTS

This work was supported by the Xunta de Galicia under projects INCITE08PXIB105161PR and 08TIC001206PR, the Ministry of Science and Innovation, cofunded by the FEDER funds of the European Union under the grant TIN2010-16735, and the Consolidation of Competitive Research Groups ref. 2010/06.

REFERENCES

Bóo, M., Amor, M., Concheiro, R., and Dogget, M. (2011). Dynamic and Adaptive Mesh Refinement on the GPU. Internal Report.

Concheiro, R., Amor, M., and Bóo, M. (2010). Synthesis of bézier surfaces. In *GRAPP'10: International Conference on Computer Graphics Theory and Applications*, pages 110–115.

Dyken, C., M., R., and Seland, J. (2009). Semi-uniform Adaptive Patch Tessellation. *Computer Graphics Forum*, 28(8):2255–2263.

Eisenacher, C., Meyer, Q., and Loop, C. (2009). Real-time View-dependent Rendering of Parametric Surfaces. In *Proceedings of the 2009 Symposium on Interactive 3D Graphics and Games*, pages 137–143.

Espino, F. J., Bóo, M., Amor, M., and Bruguera, J. D. (2007). Hardware Support for Adaptive Tessellation of Bézier Surfaces Based on Local Tests. *Journal of Systems Architecture*, 53(4):233–250.

Guthe, M., Balázs, A., and Klein, R. (2005). GPU-Based Trimming and Tessellation of NURBS and T-Spline Surfaces. *ACM Trans. Graph.*, 24(3):1016–1023.

Lorenz, H. and Döllner, J. (2008). Dynamic Mesh Refinement on GPU using Geometry Shaders. In *Proceedings of the 16-th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision 2008*.

Ni, T. and Castaño, I. (2009). Efficient Substitues for Subdivision Surfaces. Exhibition Tech. SIGGRAPH'09 Course Notes, 2009.

Piegl, L. and Tiller, W. (1997). *The NURBS Book*. Springer.

Schwarz, M. and Stamminger, M. (2009). Fast GPU-based Adaptive Tessellation with CUDA. *Computer Graphics Forum*, 28(2):365–374.