Interlocking 3D-printed bars, trusses and space frames to build arbitrarily large structures

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Abstract

It is shown that the 'Tsugite' (joint) technology used in the traditional Japanese construction method turns to be highly useful and practical in making small 3D-printed modules that can then be assembled to build arbitrarily large structures made up of bars and trusses. Of numerous variations of the Tsugite technology, we choose and focus on Okkake Daisen Tsugi, one of the most widely used methods for joining beams and columns, and study how it can be scaled down in such a way that it can be printed with low-cost FDM 3D printers using PETG and PLA filaments. Our tensile test shows that a 4.8 mm square bar with an Okkake Daisen Tsugi joint comes with a breaking load of 160–210 N. We further applied our idea to build arbitrarily large, functional 2D trusses and 3D trusses (space frames), which are expected to open up many new applications.

1 Introduction

Additive manufacturing enabled by low-cost FDM (Fused Decomposition Modeling) 3D printers opened up versatile applications by making it possible to realize complex shapes easily with good accuracy and reproducibility. It is more resource-efficient than the non-additive machining approach.

3D printing expanded the world of monolithic forming of both functional and nonfunctional components, but the monolithic approach comes with various inherent limitations, where the modular design of 3D-printed components is considered an attractive alternative for the following reasons:

scalability: The maximum print area and the print time (that could easily go beyond several hours) are obvious limiting factors of the monolithic approach, but another important factor is the increased possibility of failure that may happen for many reasons including poor first-layer adhesion and entangled/run-out filaments. Printing errors of large objects can cause enormous loss of time and resource.

functionality: Objects printed by an FDM 3D printer are inherently anisotropic. Also, orientation may greatly affect the ease of printing for objects with concavity. Therefore, many functional artifacts are ideally to be composed of a number of components with different characteristics (layer orientation, stiffness/elasticity, layer height, color, etc.) to achieve better functionality, precision, print speed, etc.

fast printing: Printing can take many hours. Modularization enables us to employ many low-cost printers to print components in parallel and reduce production time. Modularization also enables us to 'stock' standard modules beforehand.

extensibility: Modularization supports and encourages agile and incremental design by making it easy to change and/or add components for repair and function enhancement.

All these encourage us to develop and establish methodologies for combining or assembling modular components.

Combination of two contacting components comes in various forms and purposes: fixing, rotation, sliding, elastic suspension, etc. In this paper, we focus on fixing, more specifically the interlocking of components similar in size (as opposed to, say, inserting small plugs or wedges to larger components, though they are useful means of interlocking larger components).

Unlike the assembly in standard machinery and architecture, we aim at avoiding screws, nuts, nails, adhesives and welding wherever possible because

*All designs were made with OpenSCAD and are available from Github [4].

screws and nuts can slacken, adhesives can degrade, and welding makes disassembly difficult. The ideal would be to assemble components as tightly as we like only with 3D-printed parts.

The technology we are going to discuss with this motivation is the application of Japanese wood joinery (Kumiki) for modular 3D printing. Traditional Japanese architectures including historic temples and pagodas do not use bolts, nuts, or metal brackets, but they are still highly resistant to severe forces such as those from earthquakes. For Japanese woodworking in general, the readers are referred to portal websites [5][6].

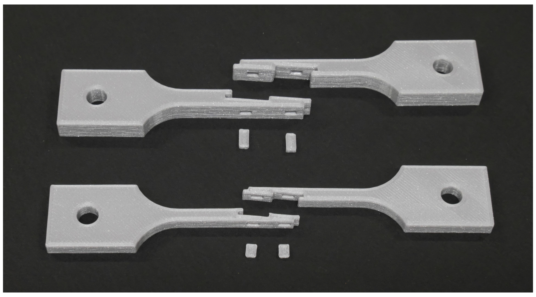
2 Interlocking Methods for 3D-printed Parts

We first briefly introduce Japanese wood joinery techniques known as Kumiki (組木) or Kigumi (木組み). They are historically referred to as Tsugite (継手) when two beams are joined straight and Shiguchi (仕口) when the beams are orthogonal or oblique. Both Tsugite and Shiguchi come in a large variety of forms [1][2]. For Tsugite, a family of techniques known as Kanawa Tsugi (金輪継ぎ), Okkake Daisen Tsugi (追掛け大栓継ぎ), and Shiribasami Tsugi (尻鋏み継ぎ), are close relatives and are known as some of the best in terms of strength compared to other alternatives including Ari Tsugi (dovetail joint) and Kama Tsugi (gooseneck joint).

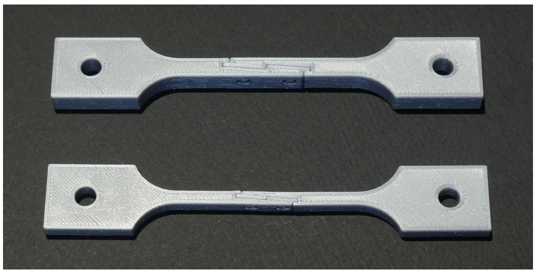
In spite of the advantages of those techniques both in aesthetics and strength, their application to 3D printing technology has not been studied in depth to the best of our knowledge. This motivated us to prototype various alternatives of Tsugite to find out promising design and parameter choices, especially for small-scale joinery. Unlike Tsugite in wood construction crafted using saws and chisels, Tsugite based on FDM 3D printing comes with its own limitations. In particular, we wish to avoid support materials for overhung parts that are sometimes not easy to remove and become garbage. Also, we wish to target on small-scale prints, say the joining of 4 mm to 6 mm square beams. Its design is worth establishing but might be somewhat different from that of wood joinery for 90 mm to 120 mm (i.e., 20 times wider) pillars and beams.

2.1 Okkake Daisen Tsugi

The technique we have chosen is called Okkake Daisen Tsugi ("Rabbeted Oblique Scarf Splice" [2] or "Rabbeted Oblique Scarf Joint"), which is one of



(a) components



(b) after assembly

Figure 1: 3D-printed Okkake Daisen Tsugi joints for 4mm and 6mm square bars

the most versatile interlocking techniques for pillars and beams in terms of very high tensile strength and reasonable bending strength. Okkake Daisen Tsugi is a scarfed joint with a slanted hook in the middle and a groove at the root, with two holes for plugs. Figure 1 shows 3D-printed components of Okkake Daisen Tsugi for 4 mm and 6 mm square bars.

The shape is basically the same as the original design for wood joinery, except that the size of the plugs and grooves cannot be scaled down proportionally from the original 15 mm. We employed the default width and height of plugs to 3 mm and 1.6 mm, respectively, and for the 4 mm bars, the height was reduced to 1.1 mm. The default width of the groove was set to 1/4 of the width of the bar.

A variation of Okkake Daisen Tsugi is Okkake Tsugi, i.e., Okkake Daisen Tsugi without plugs. This would be of practical use as long as the load applied after assembly is not large and the tightness of the joint is properly controlled.

An alternative to Okkake Daisen Tsugi for our objective would be Kanawa Tsugi (see [3] for an introduction), another popular interlocking method similar in shape. However, the ends of Kanawa Tsugi has a small overhang whose accurate printing requires support material, and unlike Okkake Daisen Tsugi, plugging is essential for Kanawa Tsugi.

Figure 2: Tensile test of 3D-printed Okkake Daisen Tsugi (4.8 mm width)

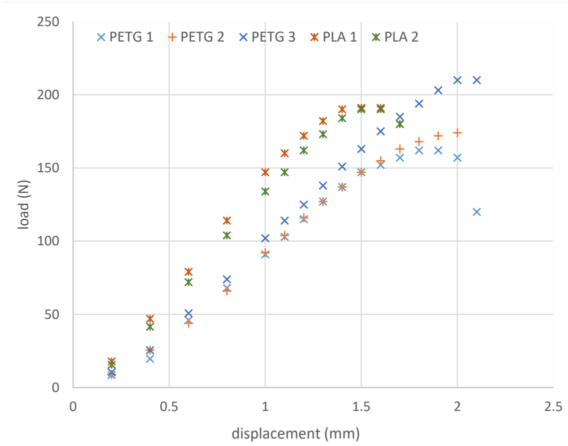


Figure 3: Tensile test results of 3D-printed Okkake Daisen Tsugi (4.8 mm width)

2.2 Strength Tests

We have conducted tensile and bend tests on 3D-printed bars (4.8 mm square) joined with Okkake Daisen Tsugi. The materials we used were Prusament PLA and SainSmart PETG filaments. We used Original Prusa i3 MK3 and with a standard 0.4 mm extrusion nozzle, 0.2 mm layer height and 80% infill. Those layer height and infill parameters were used for all prints discussed in the paper.

The tensile test as shown in Fig. 2 was made on three PETG samples and two PLA samples, and Fig. 3 shows the load-displacement characteristics of them. With a heavy load, all of them became deformed into the shape shown in Fig. 2, i.e., in such a way that the 'roots' of the joints with half the bar width became aligned in the axial direction. Four of them finally broke by unplugging, while one PLA sample broke off at the plug position of the joint (Fig. 4). Variance of the strength observed for the three PETG samples resulted from the tightness of the joints; the weakest one with a somewhat large slack could be assembled easily with fingers, while the toughest one needed a plier (or a mallet) for joining and plugging but without too much force.

For bend test, we adopted four-point bend test with the loading span of 20 mm and the support span of 80 mm (Fig. 5). The loading span was chosen so as to cover the joint area to simulate equal load over the joint part. We placed two 4.8 mm bars in parallel so that the load was applied along the y-axis (width direction or the direction of the plug) and then along the z-axis (height direction). Figure 6 shows the load-displacement curves of the tests for PETG and PLA bars. As expected, PLA

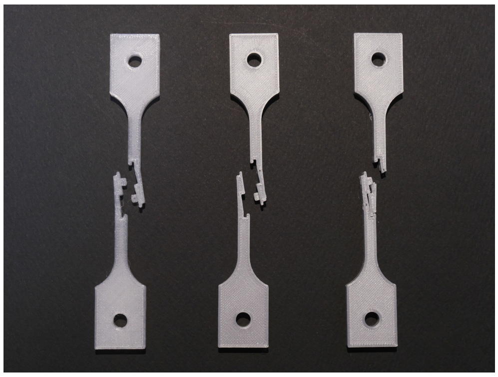


Figure 4: Joints broken by tensile test of 4.8 mm width bars (left: PETG, center and right: PLA)

was more stiff but caused breakaway at the plug position of the joint with smaller displacement. PETG was more resistant to large bend. Bending stiffness against the y-axis load was 1/2 to 2/3 of that of the z-axis load.

3 2D Truss

The initial goal of the present work was to design and implement a 3D-printable truss of arbitrary length which itself is expected to have many applications in making lightweight (and resource-efficient) functional parts.

The key idea here is not to connect member struts at the nodes of the truss but in the middle of struts. This greatly simplifies the design because nodes, a meeting point of four struts, can be printed as a monolithic part. In normal applications, nodes

Figure 5: Bend test of 3D-printed Okkake Daisen Tsugi (4.8 mm width)

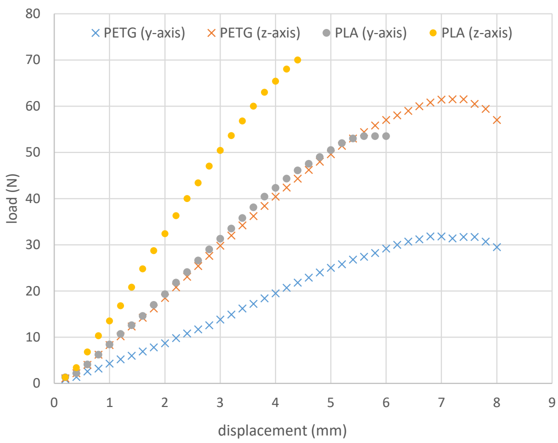


Figure 6: Bend test results of 3D-printed Okkake Daisen Tsugi (4.8 mm width)

need not be hinged because the major force born by struts are axial and the PLA/PETG struts are flexible enough to compensate the rigidity of nodes.

Figure 7 shows a module truss with 4.8 mm strut for ordinary members and 6 mm × 4.8 mm strut for joints.

3.1 Applications

In order to demonstrate the practicality of modular trusses, we have built a fully functional plotter for a large (1.5 m × 2.4 m) whiteboard, which may perhaps be one of the largest plotters available. The driving mechanism employed was CoreXY.

While we employed aluminum extrusions for upper and lower horizontal rails, the vertical rail

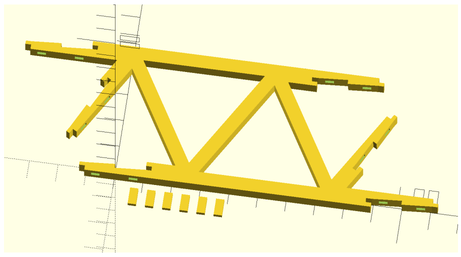


Figure 7: Truss module (4.8 mm member width; 6.0 mm joint width; 50 mm unit length)

(1.5 m long) was made by interlocking two 2D transparent PETG trusses of 50 mm unit length. The front truss (parallel to the whiteboard) was designed to work as a rail for the sliding head, while the back truss (orthogonal to the front truss) was to ensure bending stiffness of the perpendicular direction. Figure 8 shows the plotter in operation. Although the building of the plotter head was outside the scope of this paper, we note that the plotter head was assembled from over 70 3D-printed parts except for two solenoids, two switches, two pulleys, and two cable ties. We used no screws or nuts; instead we used plugs, pegs, and wedges for interlocking parts and mounting pulleys and switches.

The vertical rail weighed less than half of the aluminum T-slotted 20 mm extrusion used for top and bottom rails, and showed sufficient bending stiffness. It exhibited rather low torsion stiffness, which was coped with by controlling acceleration of the plotter head appropriately.

The plotter has been fully functional for hours, demonstrating that 3D-printed trusses are a viable and alternative to metal or wood bars and channels. In addition, their characteristics and functionalities are highly controllable and extensible.

4 3D Truss (Space Frame)

Three-dimensional trusses, also known as space frames, are widely used in construction to cover large areas (e.g., the roof of a hall) without internal supports. Geometrically, the most typical building blocks of a space frame are pyramids (half-octahedra) and tetrahedra.

Unlike 2D trusses that are rather easy to print, printing of a space frame is highly non-trivial. Firstly, each node is joined by eight member struts as shown in Fig. 9. Letting eight struts join from many directions and support them firmly is a quite complex design problem. In addition, despite its

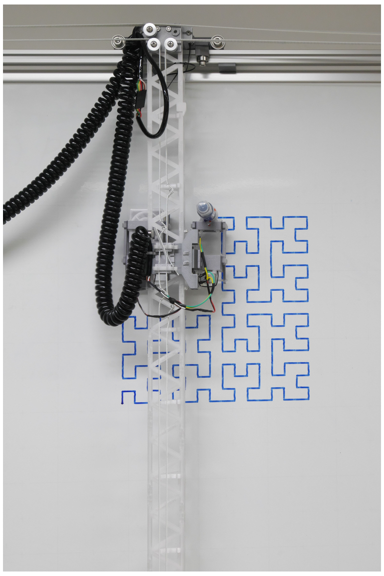


Figure 8: Whiteboard plotter with a 3D-printed truss rail

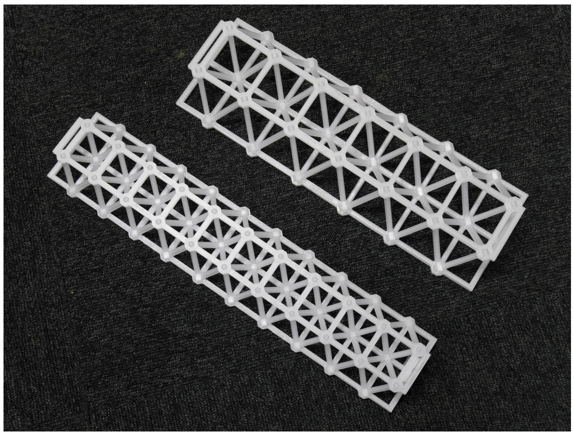


Figure 9: 3D-printed and assembled space frames ($50/\sqrt{2}$ mm (lower) and 50 mm (upper) unit length)

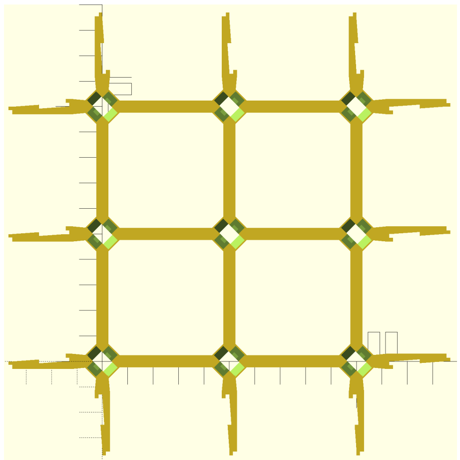


Figure 10: Upper/bottom grid module for space frame with optional joints in four directions

complexity, we would like to keep the size of a node reasonably small. Secondly, it is essential to print struts along their axial direction, which means that it is undesirable to print a node with non-coplanar struts as a monolithic part.

From the requirement on the node size and other design concerns, we again employ the idea of joining modules in the middle of struts, but still, each node is shared by eight struts belonging to three different planes.

Our solution to the above problem is as follows:

1. print each set of co-planar struts of a node (four upper/bottom struts, two diagonal co-planar struts, and the other two diagonal co-planar struts) at once,
2. interlock two pairs of diagonal co-planar struts by halving joints (Ai-Kaki Tsugi, 相欠き継ぎ), and
3. interlock horizontal and diagonal elements by “Naga Hozo Komi Sen Uchi” (長ほぞ込み栓打ち, long tenon with plugging).

More specifically, we print the components of a space frame in six groups:

1. upper grid module consisting of orthogonal struts (which may end with Okkake Daisen Tsugi joints henceforth) and mortises (rotated 45 degrees for diagonal modules),
2. bottom grid module consisting of orthogonal struts and mortises,
3. ‘outer’ diagonal module consisting of zigzag struts, long tenons (to be interlocked with upper/lower grid modules), and halving joints (to be interlocked with ‘inner’ diagonal modules),
4. ‘inner’ diagonal module consisting of zigzag struts and halving joint (to be interlocked with ‘outer’ diagonal modules),
5. plugs for interlocking mortises and tenons, and
6. plugs for interlocking modules of the same group.

Figure 10 shows a version of the upper/bottom grid module extensible to all directions, and Fig. 11 shows many possible diagonal modules.

Several remarks would be in order:

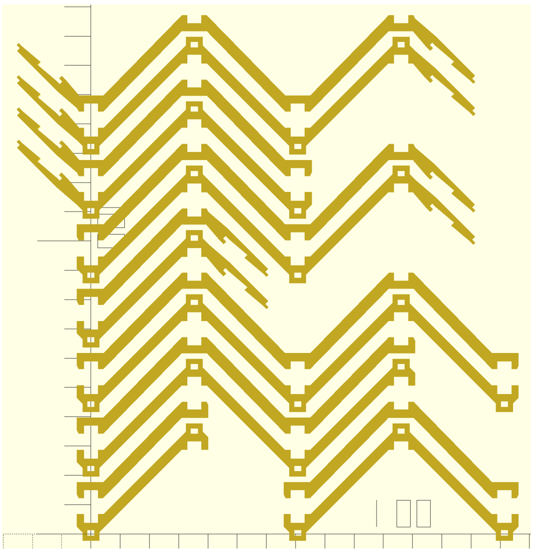


Figure 11: Diagonal modules for space frame

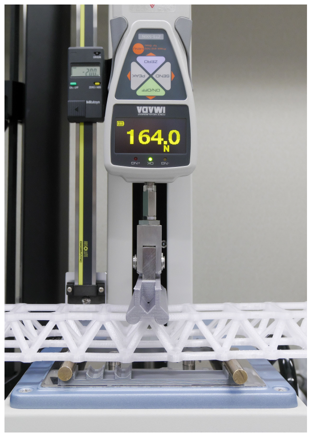


Figure 12: Bend test of a 3D-printed space frame ($50/\sqrt{2}$ mm)

- An outer diagonal module and an inner diagonal module are just joined, but the latter is confined inside outer diagonal modules which are in turn interlocked with upper and bottom modules with plugs. Thus the axial force born by diagonal members is transmitted in either direction.
- Depending on applications, interlocking plugs for mortises and tenons could be omitted, for example when the load applied is either downward towards the upper grid or upwards towards the bottom grid.
- To improve torsion rigidity (which is much weaker than flexural rigidity for space frames), we could add diagonal struts or braces to upper and/or lower grid modules to change square grids to triangular grids.

4.1 Experiments

In order to make sure this solution works in practice, we have built space frames with different sizes as shown in Fig. 9: (i) one with the unit length of $50/\sqrt{2}$ cm, unplugged, and (ii) one with the unit length of 50 mm, plugged. Both were made up of 4.8 mm square struts, except that the latter employed somewhat wider and deeper (6.0 mm×5.2 mm) joints to compensate for fragility. The node depth was the same as the strut depth for the unplugged version and was slightly thicker (5.4 mm) for the plugged version to accommodate plug holes. The size (in terms of the number of grid squares) of the test space frame was 1×10 (upper) and 2×9 (bottom) for (i), while it was 1×6 (upper) and 2×5 (bottom) for (ii). The material was PETG.

The analysis of the trusses thus formed is not as straightforward as the analysis of 'ideal' trusses found in structural mechanics textbooks for two reasons. Firstly, the nodes are interlocked by mortises, tenons and halving joints rather than hinges. Secondly, due to the small scale of the truss, the assumption that load is applied only to nodes and never to struts is not realistic. It would be more realistic to regard such trusses as materials with coarse internal structures and apply an experimental approach similar to the analysis of beams and plates.

Thus we conducted four-point bend test of the space frames (Fig. 12). Figure 13 shows the results, where the loading span was 20 mm (in order to apply uniform load to a node) and the support span was 120 mm. The figure also shows the result of three-point bend test obtained from a 9.6 mm square bar printed with 80% infill. The sectional area of this square bar is slightly less the 40% of that of each of the space frames (cut in the short-side direction). The graph of Fig. 13 shows the zone of elastic deformation and should work as a reference property for designing and analyzing space frames of different sizes and expected loads.

We made an additional bend test on the space frame with the unit length of $50/\sqrt{2}$ mm using the support span of seven units (approx. 247 mm) and confirmed that it supported at least up to 350 N of load resulting in 14 mm of displacement without breakage. We then applied even larger bending

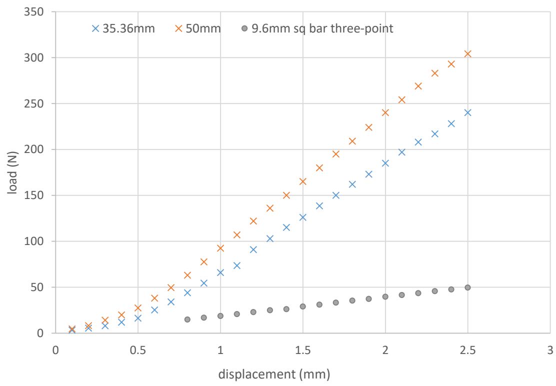


Figure 13: Bend test results of two 3D-printed space frames and a 9.6 mm square bar

load to see how the space frame could break. The breakage happened to the halving joint of diagonal modules, while Okkake Daisen Tsugi of horizontal grids just became unplugged. This is something expected, but the bottleneck of the design could thus be easily identified and improved by strengthening the point of stress concentration.

Finally, we would like to note that the broken modules could be easily removed, re-printed, and re-assembled to restore the original truss, demonstrating that our modular approach is efficient and sustainable.

5 Conclusions and Future Work

This work was initiated by several motivations that arose from our experiences with 3D printing:

1. to be liberated from the dimensional constraints of 3D printers,
2. to reduce the risk and loss due to print failures,
3. to speed up printing by parallel processing,
4. to enable agile and incremental design, and
5. to ensure extensibility, repairability, and sustainable development of 3D-printed things.

Although 3D printing enabled previously difficult monolithic forming, modularization of 3D printed components is another important direction which could perhaps be compared to the modularization of software. With this view in mind, we focused on how we could interlock two thin 3D-printed components by adapting classical but well-established wood joinery techniques to small-scale FDM settings. We have found that Okkake Daisen Tsugi of thin square bars is highly practical, natural-looking, and opens up various applications including extensible 2D trusses and 3D space frames. We actually built them and did mechanical tests.

Our final goal is the marriage of 3D printing and software engineering towards further development of the modularization, customization, and reuse of things. For instance, our open-source truss and space frame modules [4] are already parameterized, but we wish to extend them to realize trusses and space frames that are not straight or flat. The present work is our initial step. Based on our findings, we plan to develop further ideas by incorporating ideas of programming and software engineering to 3D printing.

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