Selection of Build Orientation with Minimum Tensile Strain

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ABSTRACT

Parts built from rapid prototyping processes have heterogeneous properties in both geometric form and mechanical strength. Build orientation is one of the key factors that determine how such properties are distributed in the parts. In previous studies, the selection of build orientations for the shortest build time, the best part accuracy has been reported. This study aims to investigate how to determine the build orientation so that a part built in the orientation can be subjected to the same load with the minimum deformation or strain. In the research, the selective laser sintering (SLS) technique has been used to make the test specimens. The relationships between stress/strain against build orientations are obtained through tensile test experiments. Such relationships are modeled as mathematic equations which are used for the selection of the best build orientation so that parts built in such orientation will have minimum tensile strain when subjected to the same load pattern.

Keyword: rapid prototyping, optimal build direction, tensile test.
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1 INTRODUCTION

Rapid prototyping (RP) is the technology using 3D layered manufacturing to build up the physical object. Because all objects are built layer by layer, the selection of the build orientation is crucial. It affects many key aspects of the RP process, including the part accuracy, building time, support structure, and cost of the prototype. Determining the optimal part build orientation is a difficult task as one objective always contradicts another one [7].

For a compromise of the objectives, some former researches have used multi-objective algorithms for determining the best build orientation. Cheng et al. [4] used the part accuracy as the primary objective and the build time as the secondary objective. The part accuracy weight is determined in terms of the surface types, and the build time is estimated from the number of slices. The orientation which can help the algorithm to get the maximum weight is the best one. Byun et al. [2] developed the average weighted surface roughness (AWSR) that is generated from the stair stepping effect, the build time, and the part cost using the variable layer thickness. They used the multi-attribute decision-making method, and chose the best orientation among the orientation candidates from the convex hull of a model. After some years, Byun et al. [3] also used the simple additive weighting method for the decision making considering the surface roughness, build time and part cost. And then Thrimurthulu et al. [12] used one genetic algorithm to obtain an optimum part deposition orientation for FDM process for enhancing part surface finish and reducing build time. Masood et al. [9] presented another generic mathematical algorithm, in their research, the algorithm worked on the principle of computing the volumetric error (VE) in a part at different orientations and chose the best orientation based on the minimum VE in the part. And according to Rattanawong [10], they determined the optimal orientation on the basis of the least amount of VE, too. In their technique, it involved a primitive volume approach, which considers a part to be made from a combination of basic primitive volume. Alexander et al. [1] used the cusp height to measure the accuracy of a part, and then applied to the area of each facet in the STL data to get the best orientation.

In another hand, many related works tried to change the materials to establish the part strength. Geiger and Ozel [8] added a low melting point metal alloy with the SL resin and supplementing it with cooper cooling lines. Rahmate et al. [11] found that the injection molding tool made by epoxy resins yielded higher strength. Chockalingam et al. [5] obtained some empirical relations between the strength and the process parameters, like the layer thickness, post-curing time.

Our research here is not to focus on the part characteristics of accuracy, build time, support structure, cost, or materials that have been studied previously. Instead, the build orientation of a part with the minimum strain is studied. Many experiments have been done to get the build orientation and the stress/strain relationships.

2 METHODOLOGY

2.1 Design of the Experiment

The specimens are designed based on standard tensile test specifications as shown in Fig. 1 where the dimensions are in (mm). Specimens are made to two thickness 5mm and 10mm respectively. The orientations of the samples are demonstrated in Fig. 2. In fact, the orientation is the scanning direction of each layer. The orientation is the angle between the central line and the build-up (scanning) direction of this layer in the specimen. In Fig. 3, those are the different orientations made for the experiments. Besides, we build different specimens of the orientations with different rapid prototyping techniques. Three same specimens are made in one orientation to get the accurate results. And the picture in Fig. 2 shows the three same samples in one experiment. Tab. 1 shows some important parameters of these RP techniques in our experiments.

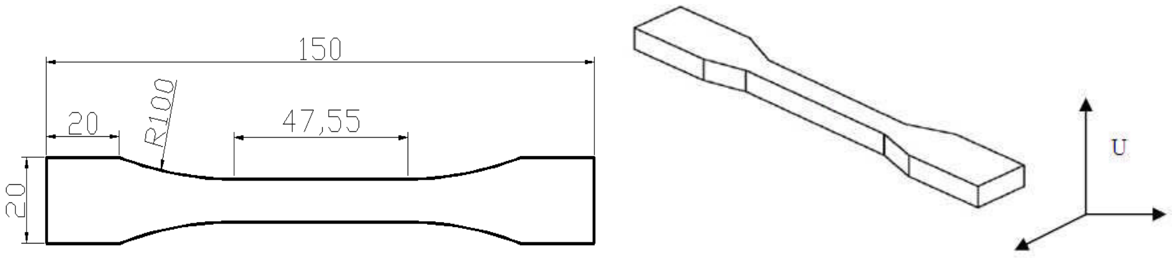


Fig. 1: A sample test specimen dimensions.

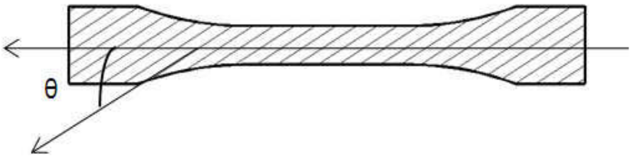


Fig. 2: The angle between the load direction (the center line) and the layer surface θ. The right one shows the specimens failure in tensile tests.

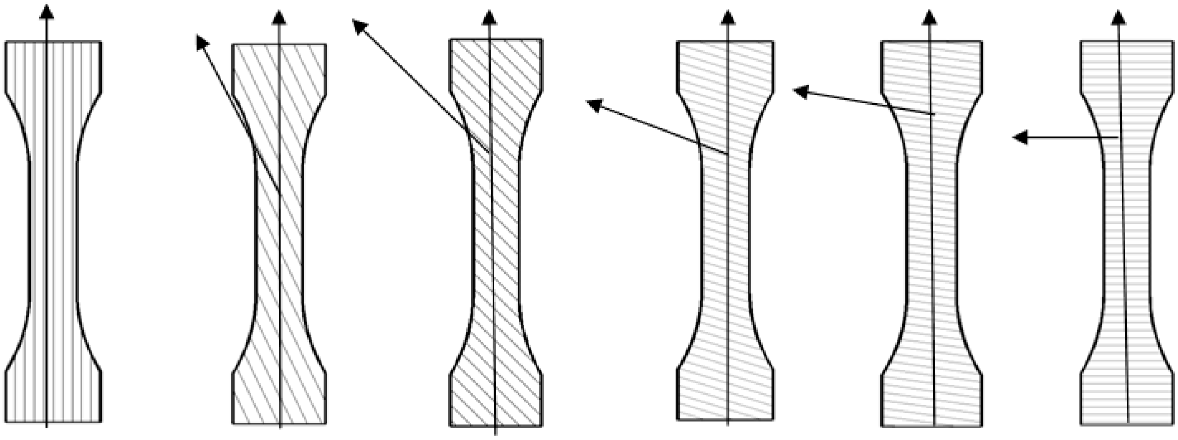


Fig. 3: The test specimens build orientations (From left to right 0°, 15°, 45°, 60°, 75°,90°).

RP Techniques	Equipment	Material	Layer Thickness
FDM	FDM 3000	ABS	0.2540mm
SLS	Sinterstation 2000	DuraForm	0.1mm
Objet	Objet EDEN 350V	Verowhite	16 ìm

Tab. 1: Process parameters of the test specimen fabrication.

2.2 Choose the Yield Point

The yield strength or yield point of a material is defined in engineering and materials science as the stress at which a material begins to deform plastically, as shown in Fig. 4. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed some fraction of the deformation will be permanent and non-reversible [6].

So, in this research, the yield points of the specimen are chosen from the graphics of the tensile test. And the stress and strain data of the yield point are considered as the maximum stress and strain of the test material in the test orientation.

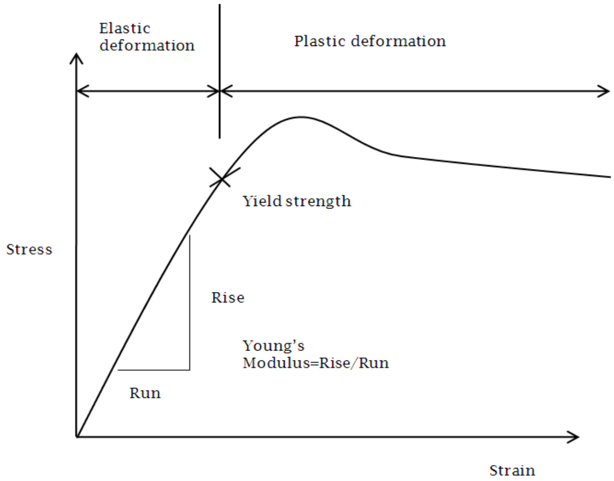


Fig. 4: The tensile test plot.

2.3 Experiments Data Process

We use the LLOYD LR 50K^{R} machine to do the tensile test. Since three specimens for every build orientation are tested, the machine output these three curves in one graphic as in Fig. 5 on the left. To get the precise data, the one that deviates more from the other two curves is abandoned. And the remaining two curves are combined to one curve using the MATLAB software as in Fig.6 on the right. Then we apply Fig.4 to get the yield point of this graphic to get the maximum strain and maximum stress and the Young's Modulus (E) of this orientation. At last, for every thickness and orientation of one rapid prototyping technique, the maximum strain-orientation, the maximum stress-orientation and the Young's Modulus (E)-orientation graphics are all obtained. For each test orientation, the maximum stress and strain of this orientation can be obtained. Fig. 6 shows the relationship between maximum stress/strain against build orientations. Besides, the formulas modeling these relationships can be obtained too. Equation one is the relationship between the orientations and the strains of these specimens. Equation two is about the orientations with the stresses, and equation three focuses on the Young's modulus (E) and the orientations. And the θ is the build-up orientation $0^\circ \leq \theta \leq 90^\circ$.

$$\varepsilon_{\max} = 0.000054\theta^2 - 0.000082\theta + 0.85 \tag{2.1}$$

$$\sigma_{\max} = 0.00021\theta^2 - 0.10\theta + 14 \tag{2.2}$$

$$E = -0.0224\theta^2 + 0.74\theta + 263 \tag{2.3}$$

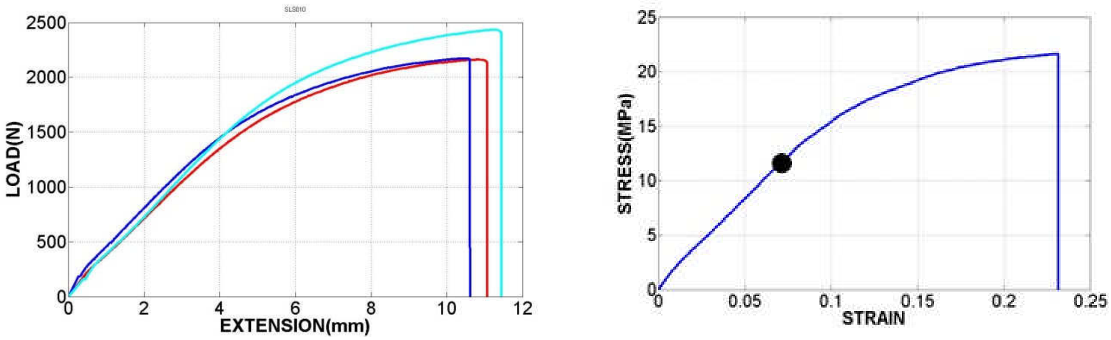
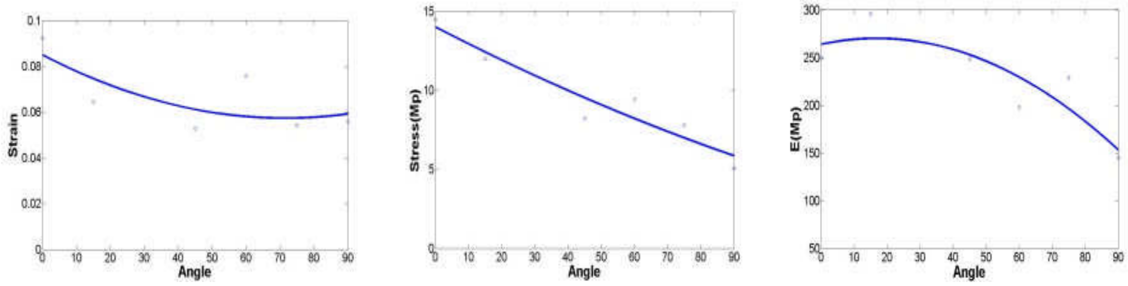


Fig. 5: The left is the Load-Extension curves, and the right is the combined one. The black point marks the yield strength.



(a) (b) (c)

Fig. 6: A sample plot for stress/strain against build orientation (SLS specimen with 10mm thickness). In Fig.7 and Fig. 8 these are the graphics of the Objet and FDM with 10 mm thickness.

3 DECISION CRITERIA AND APPLICATION

3.1 Decision Criteria

As mentioned before, prior to the yield point the material will deform elastically and will return to its original shape. Hence, the constraints are all about the strains of the parts stay in the area of the elastic deformation. That means the strains are all less than the values of the yield points. Here we discuss about the model that is under one constant load.

Fig. 7 shows a model built from different ways. For the left model, it can be built up as an assembly at one time; it also can be assembled after each links are built. We will talk about the two scenarios.

3.1.1 Model Built up Separately.

The Elastic deformation is reversible, so the strains must be controlled under the max elastic deformation strain. The constraints are:

$$\varepsilon_{\mathrm{n}} < \varepsilon_{n\max} \tag{3.1}$$

For each link of the model, the direction of the load is along the center line. And the strain of a link can be written as:

$$\varepsilon_n = \frac{K_n P L_n}{EA} \tag{3.2}$$

In this formula, K_n is used as the coefficient to determine the force of a link. P is the force that loads on the whole model. So, $K_n P$ means the force for a link. L_n is the valid length of the part in the tensile test. E is the Young's modulus. A is the cross section area of the part. Eqn (3.2) can be simplified as:

$$\varepsilon_n = \frac{K_n}{E} \tag{3.3}$$

k_n sums up the information that is irrelevant to the build-up orientations of a link, and E is the Young's modulus, and the value of E can be gotten from the curve in the tensile experiments. The minimum strain is determined by the E. Hence, the minimum strain happens when the E gets the maximum value.

3.1.2 Model Built as a Single Part

The constraints are the same as the first one scenario,

$$\varepsilon_{\mathrm{n}} < \varepsilon_{n\max} \tag{3.4}$$

However, the criteria to decide the orientation are different from above.

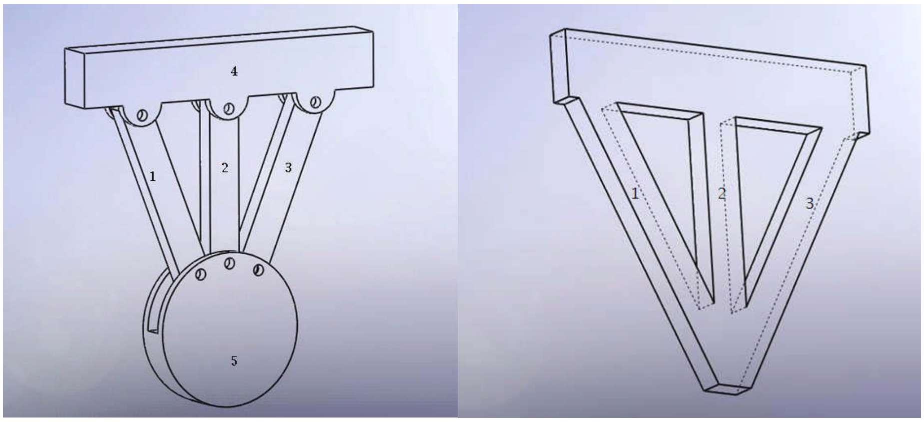
Since the model is built as a single part in one set-up, the whole model is considered other than each link considered individually. In the structure, it is impossible for each link to get the best orientation. The equation below is used to calculate the strain.

$$\varepsilon = \sum_{m=1}^{n} \frac{K_m}{E_m} \tag{3.5}$$

K_m means the sum of the information that is irrelevant to the build-up orientations of this part, and now we use the E_m instead of E in equation 3.3. That is because the model is built up as a single part. Every E of each part is relative to each one. And the orientation that gives the minimum ε is the one we want.

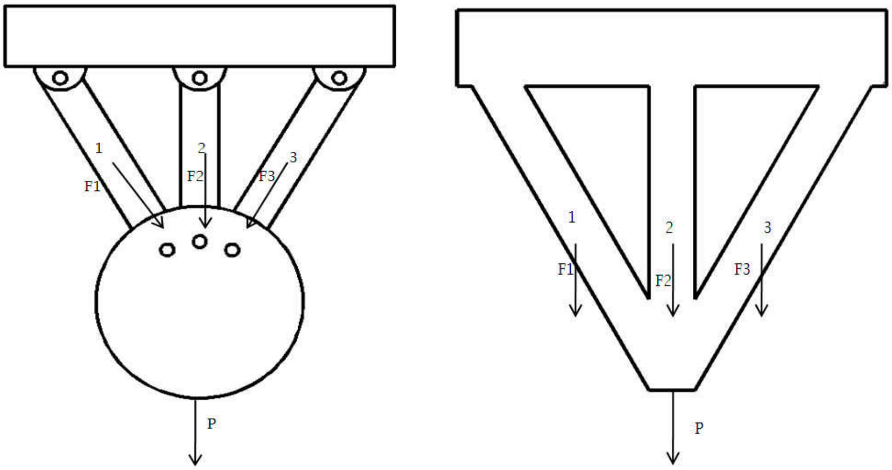
3.2 A Case Study

Fig. 9 shows the models designed for the case study. In Fig. 7(a), the model is composed of an assembly with three links labeled 1, 2, 3. Each link is defined by its length*width*thickness (mm). In this study, the dimensions for the three links are 80x15x10, 70x15x10, and 80x15x10 for links 1, 2 and 3 respectively. The angle between link 1 and link 2, link 2 and link 3 is 30°. Now, suppose the top bar of the structure is fixed, and a load of 100 N is applied as shown in the Fig. 8. The following is the analysis of optimal build orientation for the two structures.



(a) (b)

Fig. 7: The test parts.



(a) (b)

Fig. 8: The forces on the links.

3.2.1 For Hinged Structure

For the model in Fig.7 (a), it has five major parts as marked. Using rapid prototyping processes, the model can be made in two different ways. The first is to fabricate the five parts separately and assemble them after fabrication. The second is to fabricate the structure as an assembly with no need to assemble them after fabrication (in-assembly fabrication). The optimal build orientation for the two methods is different.

Fabricate and assemble:

The five parts are made separately and assembled as one whole model.

The constraints are:

$$\begin{aligned} \varepsilon_1 &< \varepsilon_{1\max} \\ \varepsilon_2 &< \varepsilon_{2\max} \\ \varepsilon_3 &< \varepsilon_{3\max} \end{aligned} \tag{3.6}$$

The key formula to decide the orientation:

$$\varepsilon_n = \frac{K_n}{E} \tag{3.7}$$

From the above equations, we can easily get that, when α =17°, these three parts can get the minimum strain. This orientation means the angle between the central line and the build-up direction as shown in Fig. 9.

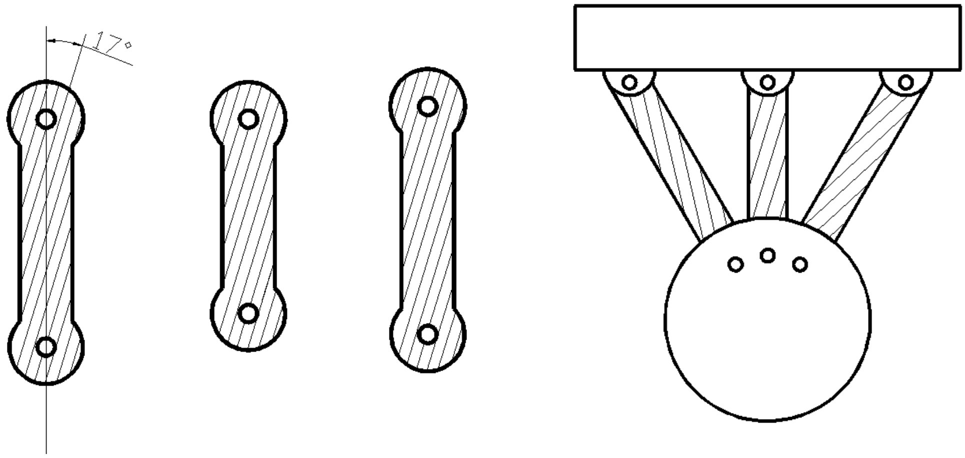


Fig. 9: Build orientation with individual link fabrication.

In-assembly fabrication

The whole model is built as an assembly

The constraints are:

$$\begin{aligned} \varepsilon_1 &< \varepsilon_{1\max} \\ \varepsilon_2 &< \varepsilon_{2\max} \\ \varepsilon_3 &< \varepsilon_{3\max} \end{aligned} \tag{3.8}$$

$$\varepsilon = \sum_{m=1}^{n} \frac{K_m}{E_m} = \frac{K_1}{E_1} + \frac{K_2}{E_2} + \frac{K_3}{E_3} \tag{3.9}$$

After the calculation, the minimum ε is 9°. The orientation means the angle between the central line of the center part and the build-up line, as shown in Fig. 10(a).

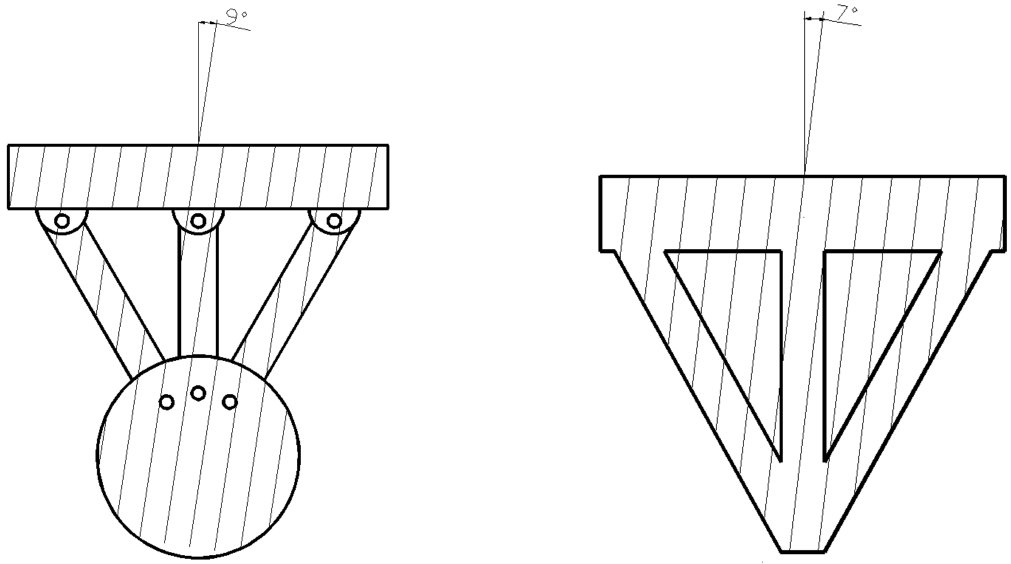
3.2.2 Fabricated as a Single Part

The constraints are the same as the first one with the second method; the different between these two are the directions of the force loaded in the three parts, as shown in Fig. 8.

However, the key formula is applied in the same way, but K_1 , K_2 , and K_3 are different for the different directions of the loads.

$$\varepsilon = \sum_{m=1}^{n} \frac{K_m}{E_m} = \frac{K_1}{E_1} + \frac{K_2}{E_2} + \frac{K_3}{E_3} \tag{3.10}$$

From the calculation, when the angle is 7 °, we can get the minimum □. And the orientation means the angle between the central line of the center part and the build-up line, as shown in Fig. 10(b).



(a) In assembly fabrication (b) Single part fabrication

Fig. 10: The build-up orientations of two cases.

4 CONCLUSIONS

Part build orientation is one of the most important factors considered in the RP process. Previous papers about optimal build orientation have not considered load capacity. This paper presents a new method for determining the optimal build orientation based on a given load pattern. In the paper, only the minimum strain is considered. In the future, other load factors will be set as an objective for optimization. A case study has been used to illustrate how to determine the optimal build orientation for a structure.

As another future work, the structure shown in this study will be built using three RP processes to verify the theoretical results presented in this paper. More complicated structures under various load patterns will be studied too.

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