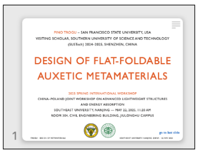
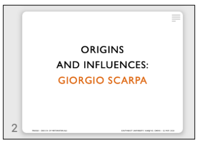
Design of Flat-Foldable Auxetic Metamaterials



1. Hello everyone, my name is Pino Trogu and I am a teacher at San Francisco State University. I am honored to be presenting here today and I would like to thank Southeast University and in particular Prof. Qai and Prof. Kim for inviting me.

The work I will show you today has its roots almost fifty years ago when I was a high school student but it's been an important part of my academic life especially in the last ten year. I will first tell you about the pioneering work of one of my teachers. Then I will show you how that work has intersected and inspired my own work in relation to some recent advances in the field of so-called metamaterials.

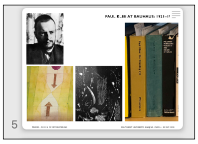
I am hoping that this work, and the particular prototypes you will see can be a small contribution to this field. I will try to keep my talk short so that we can have some time to play and interact with the actual physical models. I will bring back the models to the Q&A session tomorrow morning so please come back tomorrow to continue the conversation. First let me clarify my title a bit: metamaterials is the name that has stuck for advanced materials that derive their properties more from their geometry than from their chemistry; auxetic means that these materials behave the opposite of for example a rubber band that's being stretched, in that in their case they get thicker instead of thinner; and flat-foldable is of course nice to have for all kinds of practical reasons.



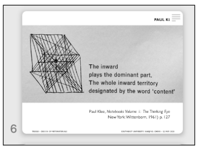
2. So, my teacher's name was Giorgio Scarpa.

3. Scarpa started out as a painter but later turned to geometric structures and their parallel in biology. His day job, luckily for us students, was teaching technical drawing at the Art Institute in Sardinia, Italy.

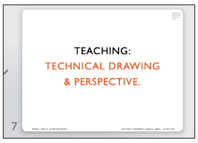
4. While geometry was perhaps more technical, art and aesthetics remained important aspects of his exploration.



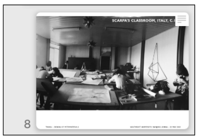
5. He mentioned to me once that the Swiss painter Paul Klee, whose Bauhaus lectures he studied, was a big inspiration for his own studies of geometric models.



6. Like for example this beautiful caption for a sketch of the internal planes of a cube, where the word "content" takes on multiple meanings which invite and encourage curiosity.

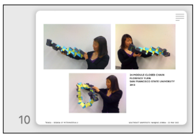


7. Besides drawing and perspective, his lessons often involved model making and geometric dissections.

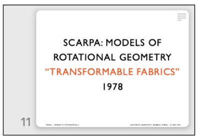


8. His classroom was a lot of fun, with models everywhere almost like a nature lab.

9. I still teach one of his projects to my students, where they have to section a cube in two or three identical parts.



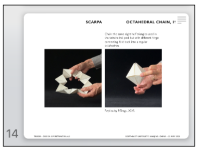
10. Once in a while an adventurous student will connect the parts to form modular chains that can rotate and transform.



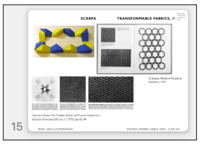
11. Already in the 1970s Scarpa would discuss his models of rotational geometry in terms of “transformable fabrics”, as if he were discussing today’s origami and metamaterial structures.

12. Because of time and fabrication constraints, his scaled models, like the one shown on top left, often remained on paper. Making physical models of these designs found in his published book is one of my current interests.

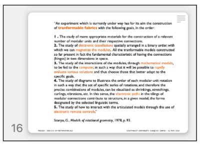
13. At SUStech in Shenzhen where I am currently on sabbatical, I have been working with students to explore the potential applications of these innovative shapes.



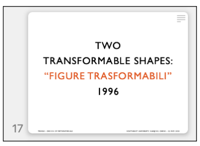
14. With reconfigurable robots these days being obvious choices.



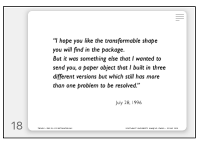
15. At top right, this double page from his book, showing microphotographs of proteins on the left page leaves no doubt that his idea of “transformable fabrics” related to biology. The Italian word for “fabric” is “tessuto” which also means “tissue”.



16. In 1978 Scarpa speaks of these transformable fabrics in terms of electronic tessellations and modular magnetization, and of electronic paths and remote controls in ways that today are clearly associated with actuators and intelligent robotics.



17. In 1996 Scarpa invented two “transformable shapes” which are key to the metamaterials that will be shown shortly, although I was aware of just one at the time, and discovered the second only in 2017 after his death.

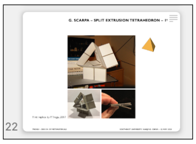


18. His letter from that time mentions the second mysterious shape but that was it! He never returned to the subject.

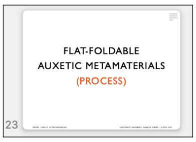
19. The first, a prismatic cube, was actually found in 1926 by the mathematician J.F. Petrie, with Scarpa unaware of this precedent. The shape forms one of only three regular honeycombs.

20. Then in 2016, Bas Overvelde and others, themselves unaware of Scarpa's model, published the first of their three "prismatic metamaterial" articles featuring the same shape.

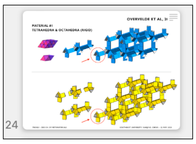
21. By now you are probably wondering if the mystery shape is ever gonna show up — but we are very close: a year later Overvelde's follow-up article in *Nature* on "architected materials" gave me the clue I needed to see what was actually in front of my eyes.



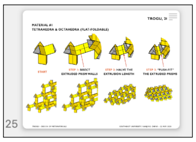
22. I had seen it many times before, on a shelf in Scarpa's studio: a tetrahedron, or triangular pyramid, with its faces extruded and its walls bisected.



23. So how do you put Overvelde and Scarpa together?

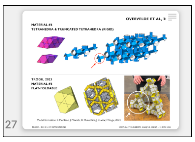


24. While many of Overvelde's honeycombs can transform beautifully, others are partially or fully rigid on account of the presence of triangular prisms which are rigid by definition.

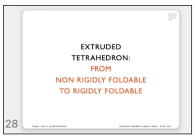


25. Now, it turns out that adding the extra Scarpa crease allows these previously rigid honeycombs to become flexible. Here, besides adding the bisections in step 1, I halved the extrusion lengths in step 2, and further halved them in step 3.

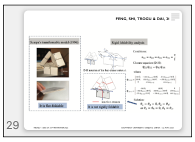
26. This physical model is a 3x3x3-tetrahedra cubic patch of the same honeycomb we call Material #1.



27. I also made a physical model of Material #6 which is related to Material #1 and was originally rigid but is now flexible.



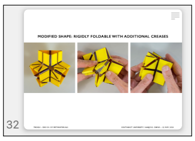
28. So far I have only published the single extruded shape in the proceedings of the 2024 ReMAR conference on reconfigurable robots.



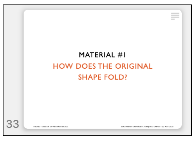
29. In which we show that the original shape is not rigidly foldable…

30. That it folds due to some hinge deformations …

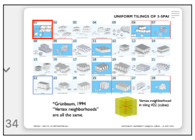
31. And that it can rigidly fold if diagonal creases are added to some of the square plates…



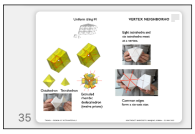
32. Thus admitting only rigid pates and rotational hinges.



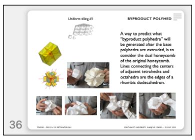
33. But the question is how does the original shape fold?



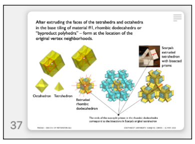
34. A step back is needed to look at the base 3D tilings from which the honeycombs are built. The tilings are called uniform because (1) All the solids used in them fit perfectly into spheres and (2) All the solids' shared groups of vertexes repeat exactly the same throughout the materials.



35. It turns out that when the solids are moved apart and extruded, new solids arise at those original vertex locations. In Material #1 that shape turns out to be a rhombic dodecahedron.

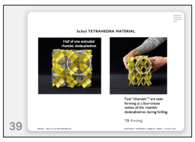


36. It further turns out that one can predict what that new shape will be by connecting together the centers of all the solids surrounding a common vertex. This is convenient because that shape is the single building block one needs to form the entire material.



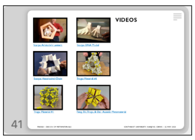
37. And so, Material # 1 can be made just by connecting together a bunch of extruded rhombic dodecahedra where the connections are the original Scarpa creases.

38. This model tries to visualize this rather complicated-sounding process which I am sure will be simpler after you handle the models directly.

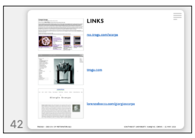


39. When the material folds, some of the extruded prisms align themselves into a simpler looking traditional honeycomb core…

40. With that alignment corresponding to the 4-crease vertex axis in the rhombic dodecahedron.



41. Later I can share the links to some videos…



42. … while these are some web resources…

43. Thank you so much for your patience. We can now look at the real models and I hope I can answer some questions today and also tomorrow during the Q&A.