Title: Impossible Crystals

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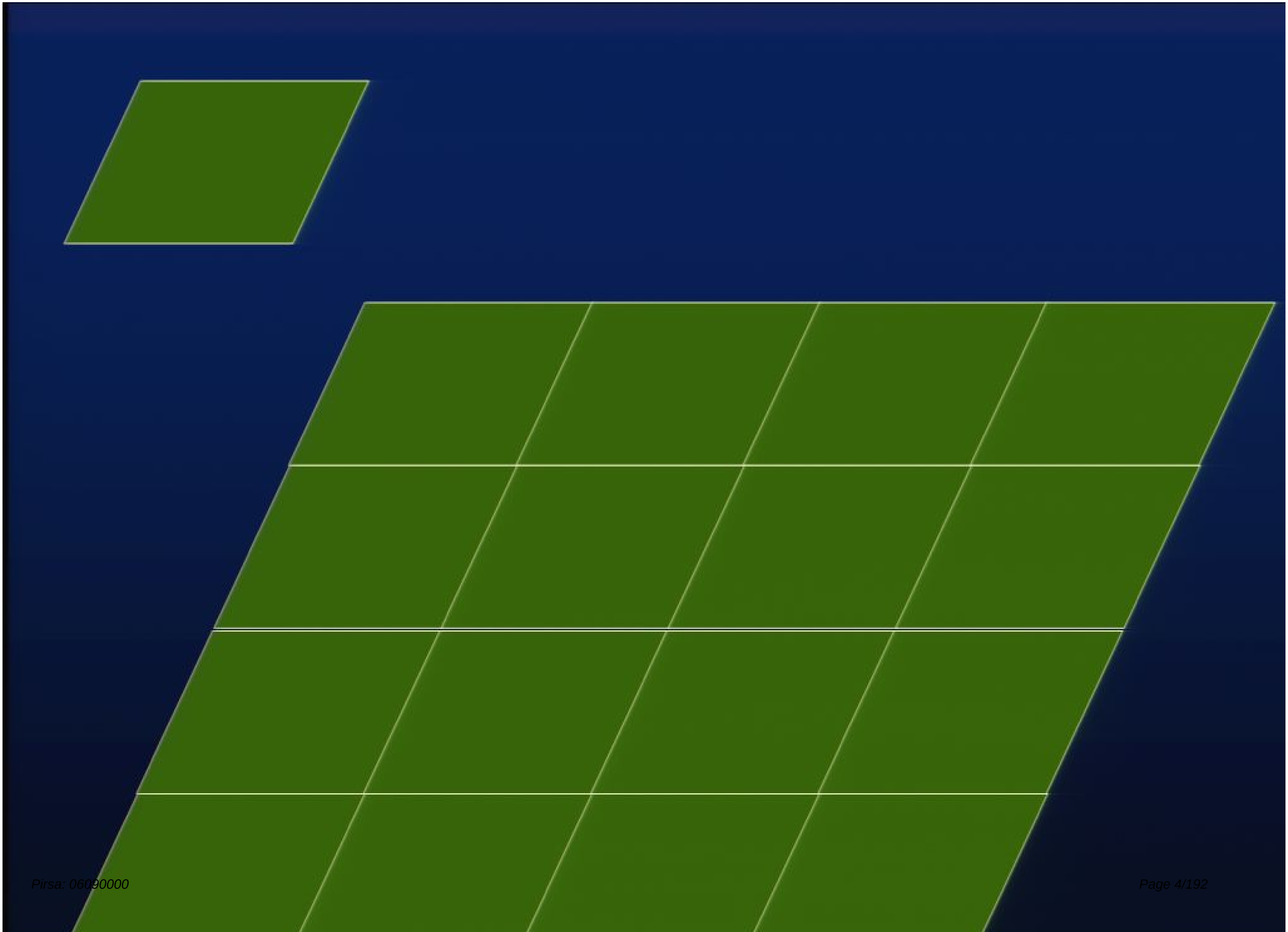
Abstract: This is a story of how the impossible became possible. How, for centuries, scientists were absolutely sure that solids (as well as decorative patterns like tiling and quilts) could only have certain symmetries - such as square, hexagonal and triangular - and that most symmetries, including five-fold symmetry in the plane and icosahedral symmetry in three dimensions (the symmetry of a soccer ball), were strictly forbidden. Then, about twenty years ago, a new kind of pattern, known as a \'quasicrystal,\' was envisaged that shatters the symmetry restrictions and allows for an infinite number of new patterns and structures that had never been seen before, suggesting a whole new class of materials. By chance, solids with five-fold symmetry were discovered in the laboratory at about the same time. Even so, for nearly twenty years, many scientists continued to believe true quasicrystals were impossible because, they argued, such a pattern could only be formed with complex and physically unrealistic inter-atomic forces. In this talk, you will see simple, beautiful patterns and a series of geometrical toys and games that demonstrate, with subtlety and surprise, how this last conceptual barrier has been recently overcome - leading to new insights on how to grow perfect quasicrystals and inspire new technological applications. About the Speaker: Paul J. Steinhardt is the Albert Einstein Professor in Science at Princeton University and is on the faculty in the Department of Physics and in the Department of Astrophysical Sciences. He received his B.S. in Physics at Caltech in 1974; his M.A. in Physics in 1975 and Ph.D. in Physics in 1978 at Harvard University. He was a Junior Fellow in the Harvard Society of Fellows from 1978-81 and on the faculty of the Department of Physics and Astronomy at the University of Pennsylvania from 1981-98, where he was Mary Amanda Wood Professor from 1989-98. He is a Fellow in the American Physical Society and a member of the National Academy of Sciences. In 2002, he received the P.A.M. Dirac Medal from the International Centre for Theoretical Physics. Steinhardt is a theorist whose research spans problems in particle physics, astrophysics, cosmology and condensed matter physics. He is one of the architects of the .inflationary model. of the universe, an important modification of the standard big bang picture which explains the homogeneity and geometry of the universe and the origin of the fluctuations that seeded the formation of galaxies and large-scale structure. He introduced the concepts of .quintessence,. a dynamical form of dark energy that may account for the recently discovered cosmic acceleration. He has also explored novel models for dark matter. Recently, Steinhardt and Neil Turok (Cambridge U.) proposed the .cyclic model. of the early universe, a radical alternative to big bang/inflationary cosmology in which the evolution of the universe is periodic and the key events shaping the large scale structure of the universe occur before the big bang. In condensed matter physics, Steinhardt and Dov Levine (Technion) introduced the concept of quasicrystals, a new phase of solid matter with disallowed crystallographic symmetries. Steinhardt continues to make contributions to understanding their unique mathematical and physical properties. He has written over 200 papers, edited 4 books, and holds three U.S. patents. <kw> Impossible Crystals, Paul Steinhardt, symmetry, crystal, three-fold symmetry axis, five-fold symmetry axis, two-fold symmetry axis, quasicrystals, rotational symmetry, Penrose, Penrose Tiler, Gummell-Tile, quasi-unit-cell, non-local iterations, period array, platonic crystal </kw>

Prologue



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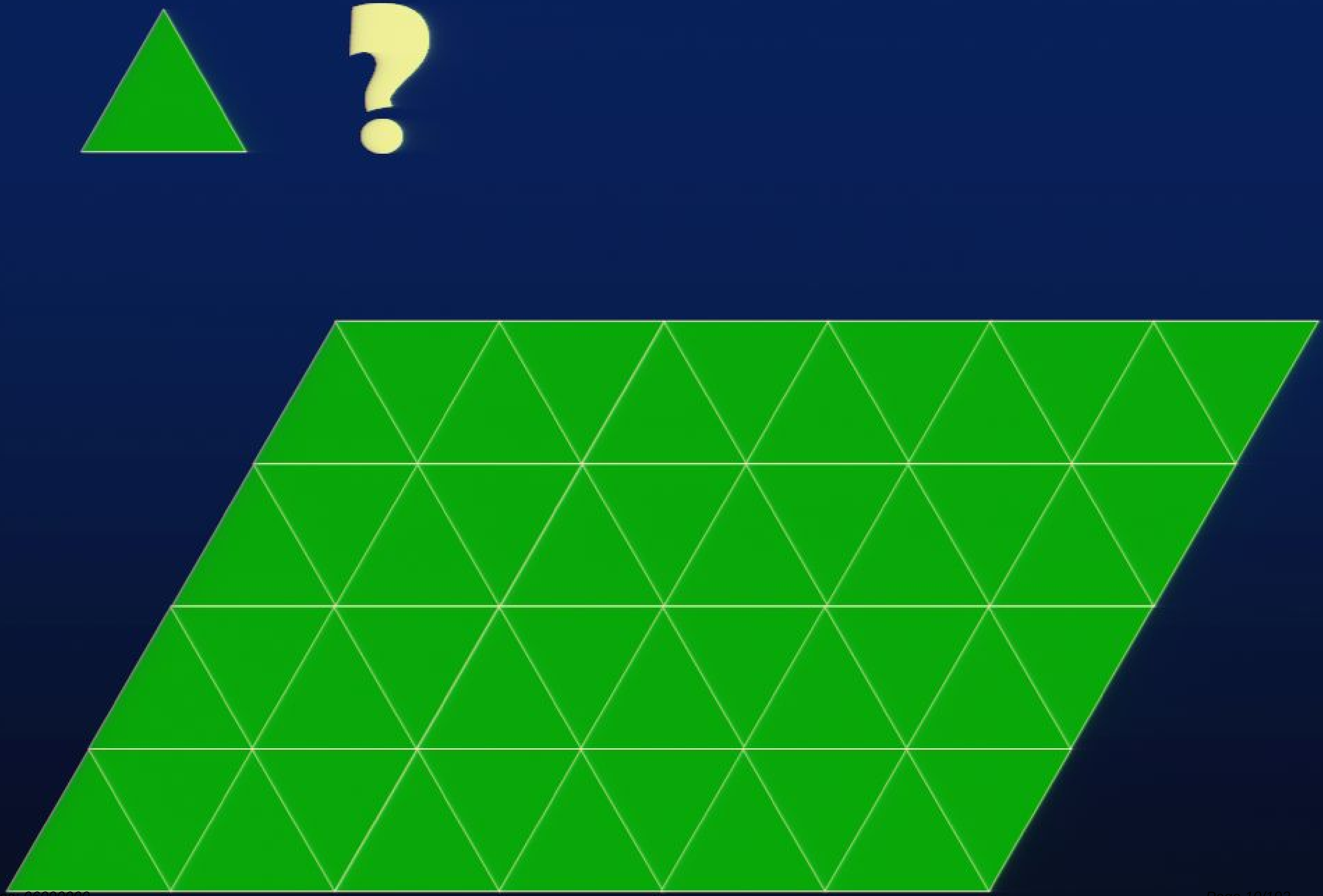

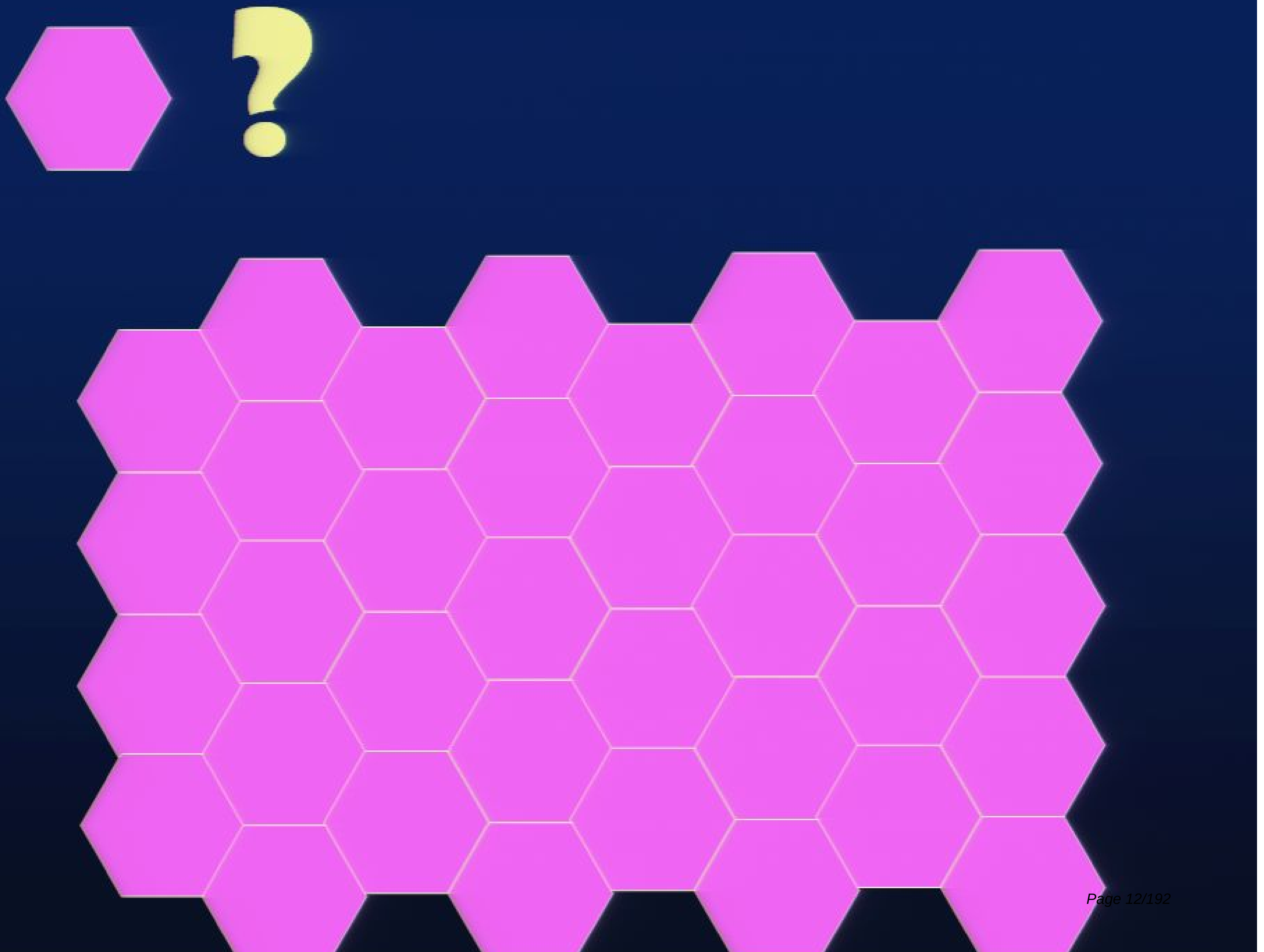

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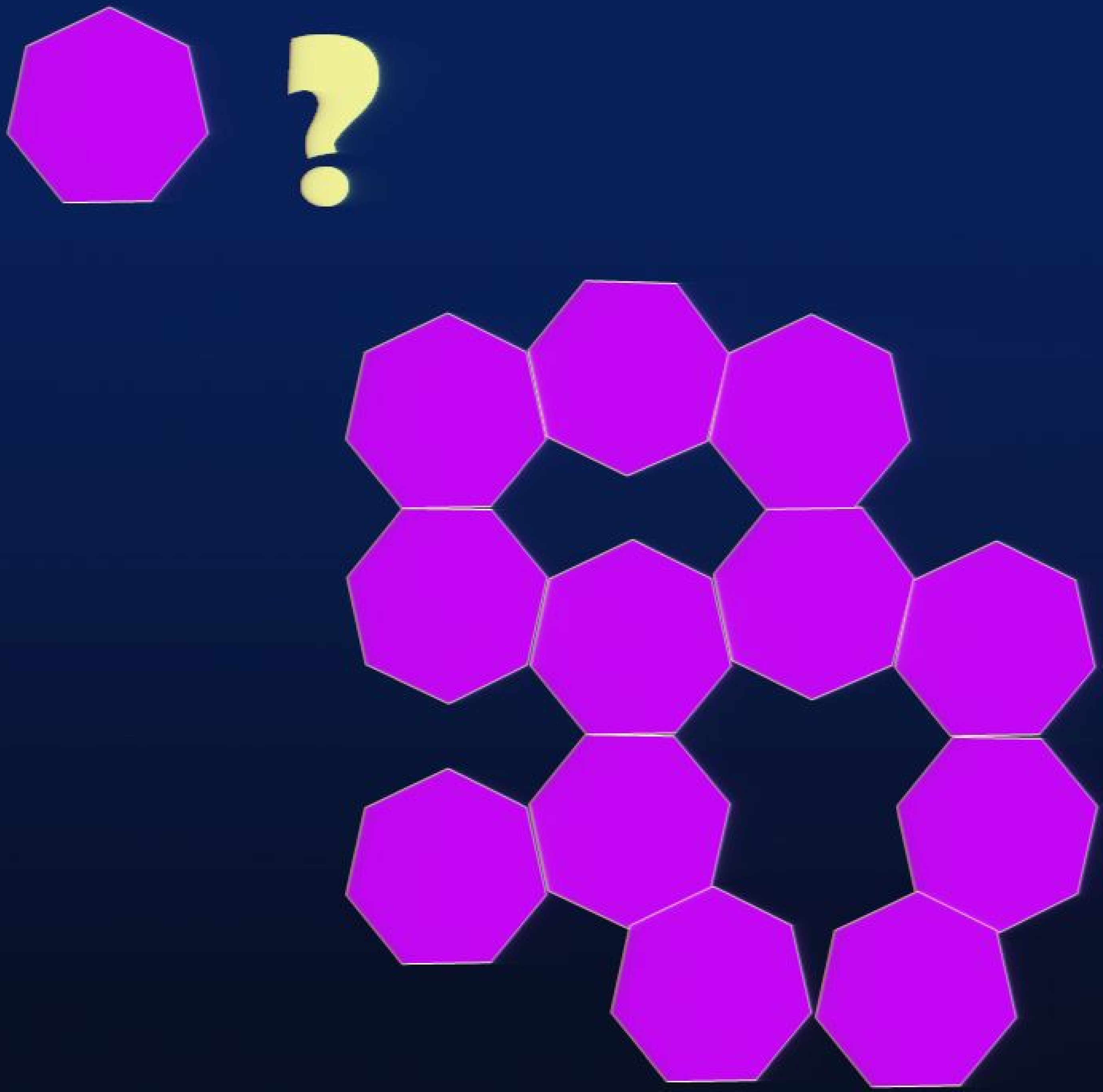
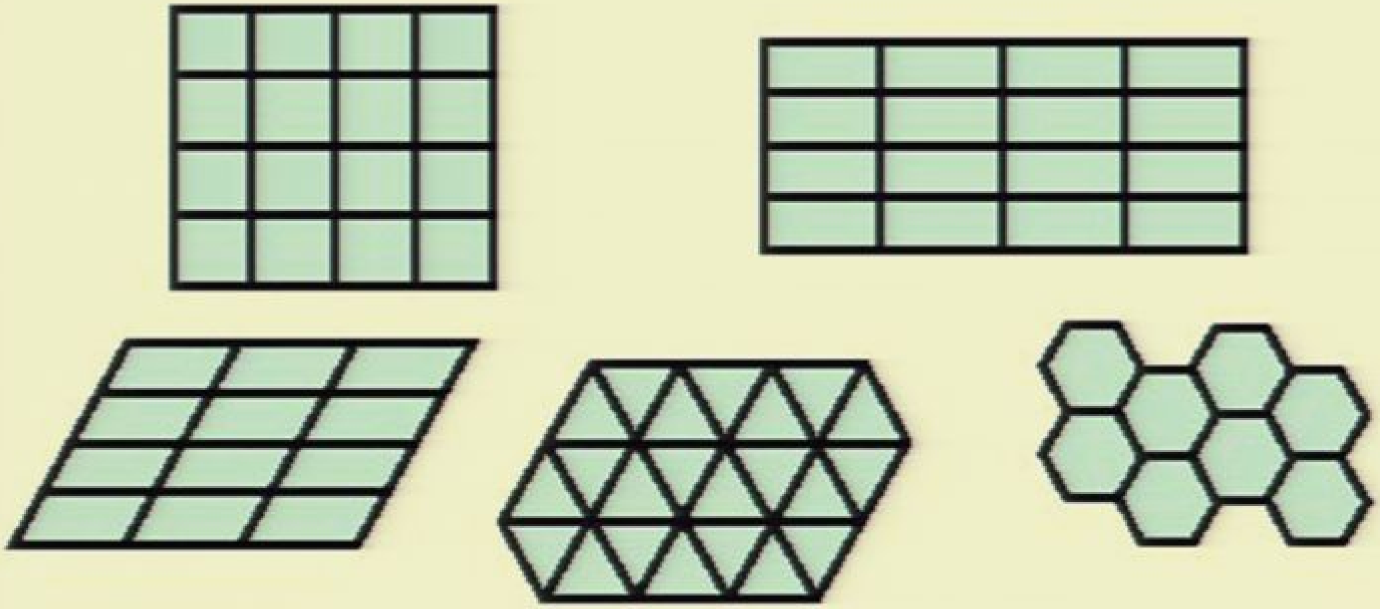
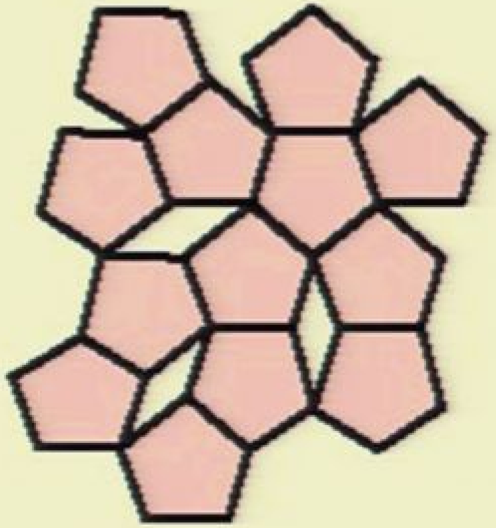


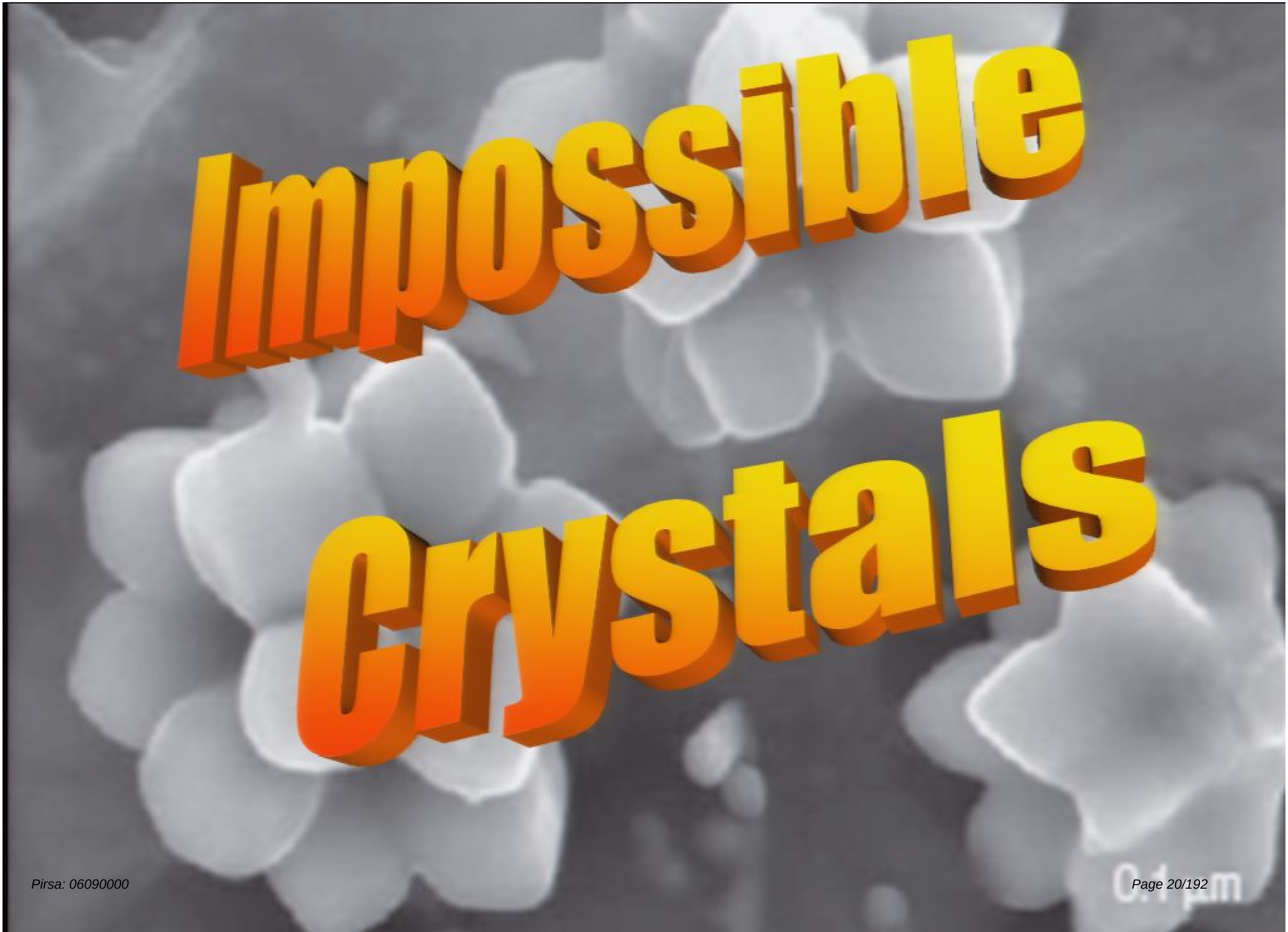


Symmetry Axes
Compatible
w / Periodicity



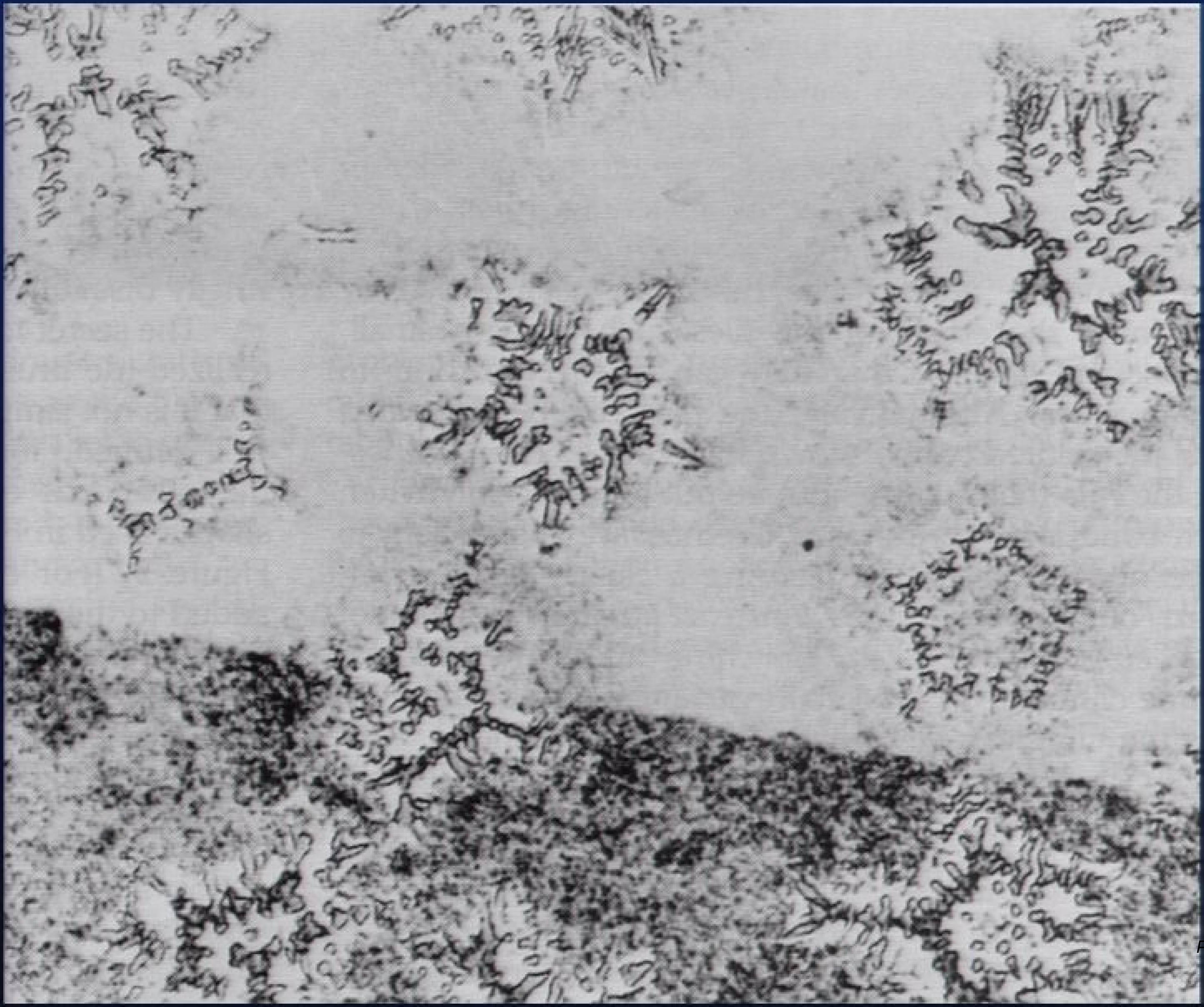
5-fold
Symmetry is
FORBIDDEN

Impossible Crystals



D. Shechtman, I. Blech, D. Gratias, J.W. Cahn (1984)

Al_6Mn



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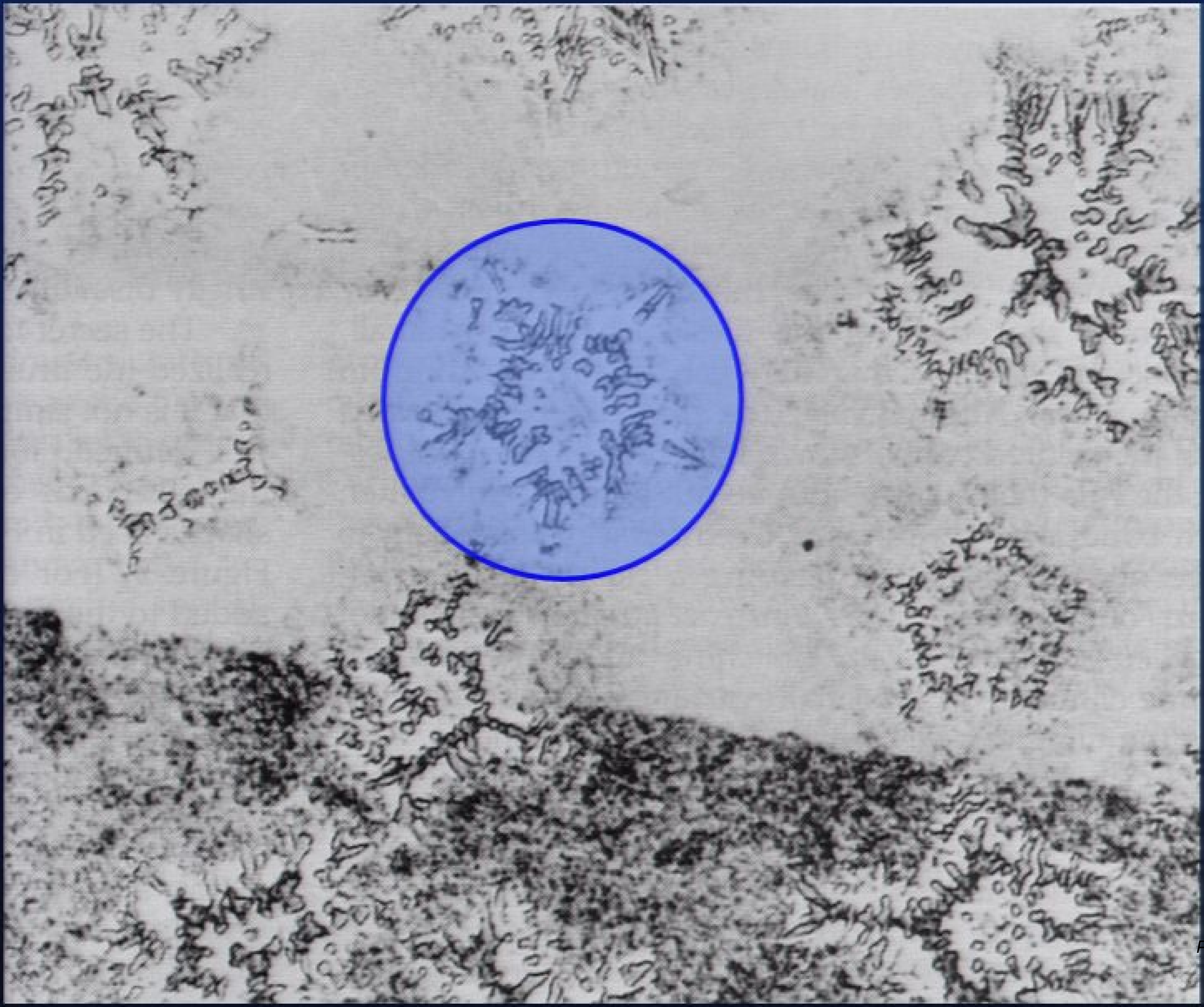

D. Shechtman, I. Blech, D. Gratias, J.W. Cahn (1984)

“Diffracts electrons like a crystal . . .
But with a symmetry <u>strictly forbidden</u> for crystals”

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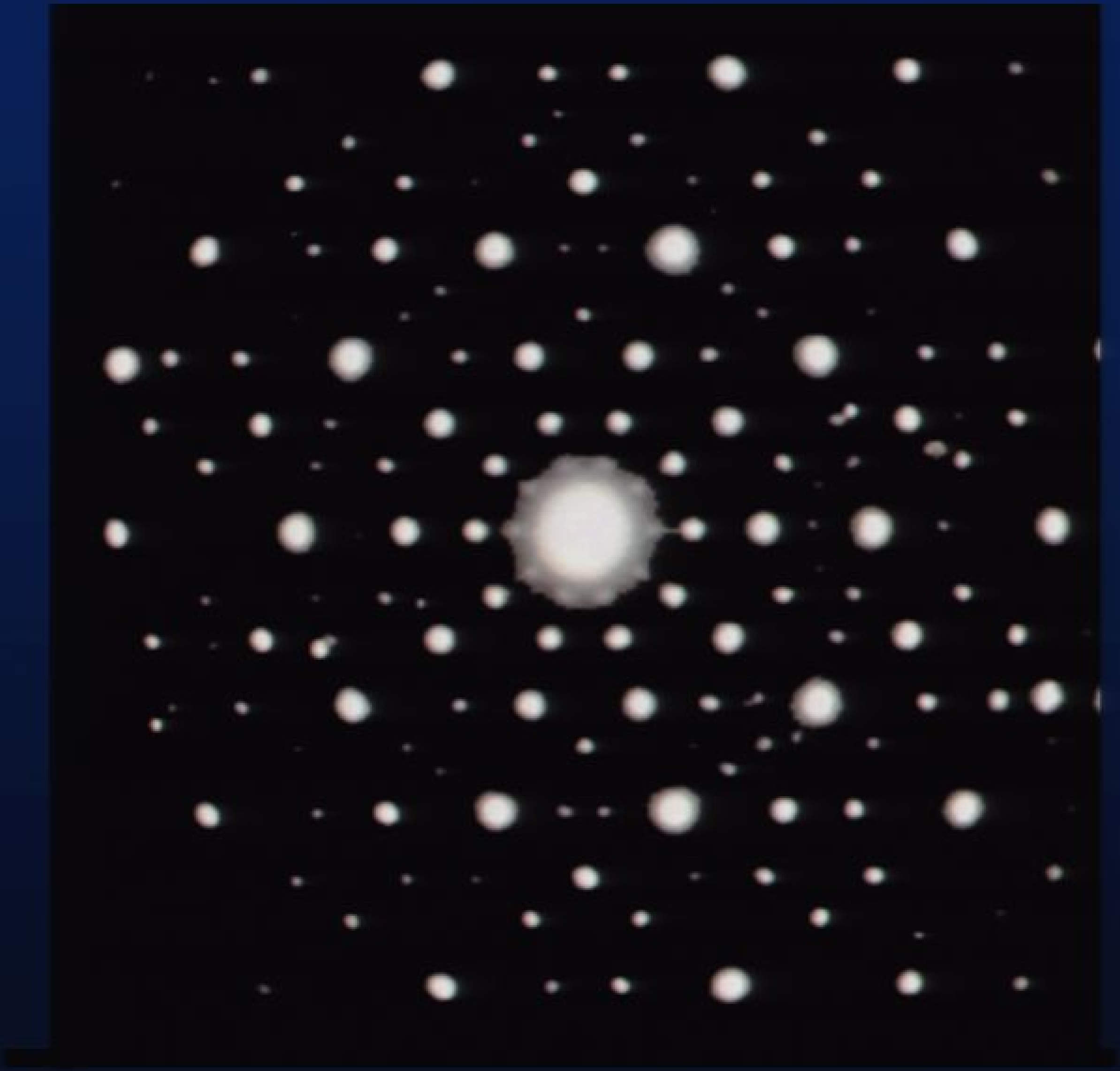

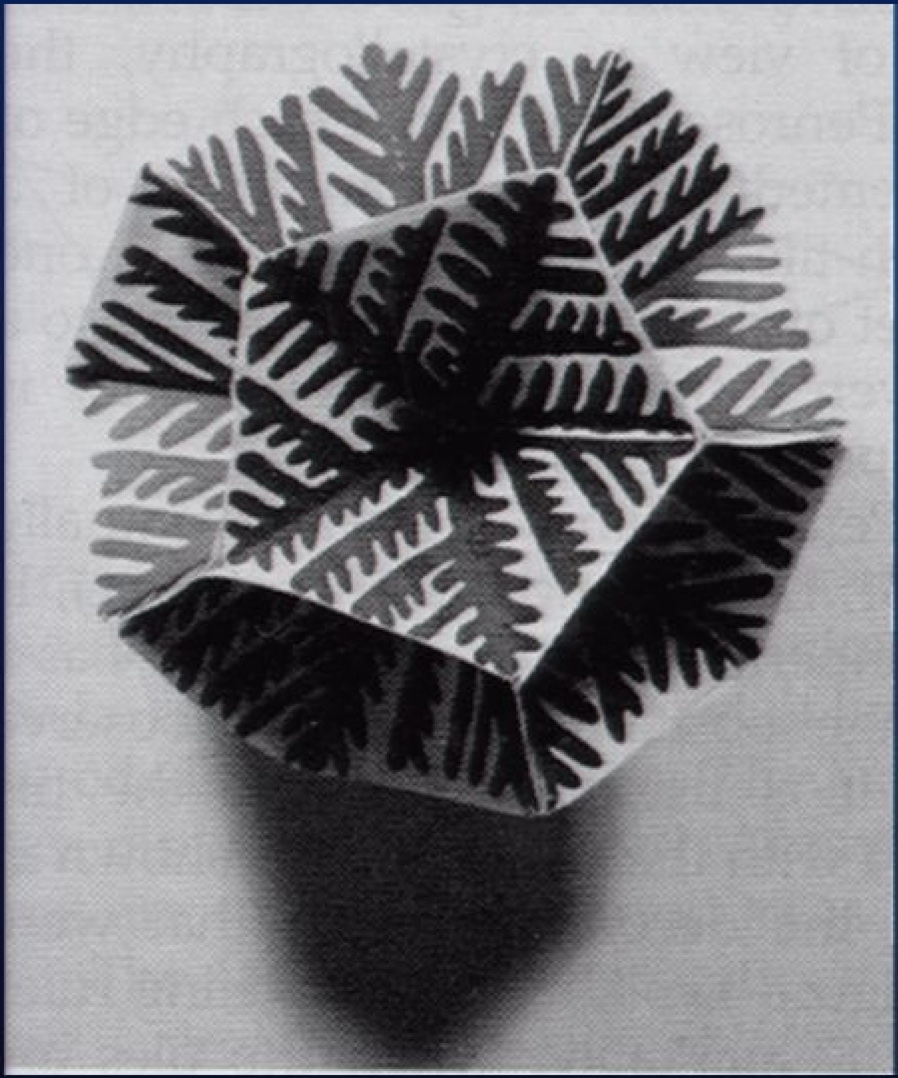

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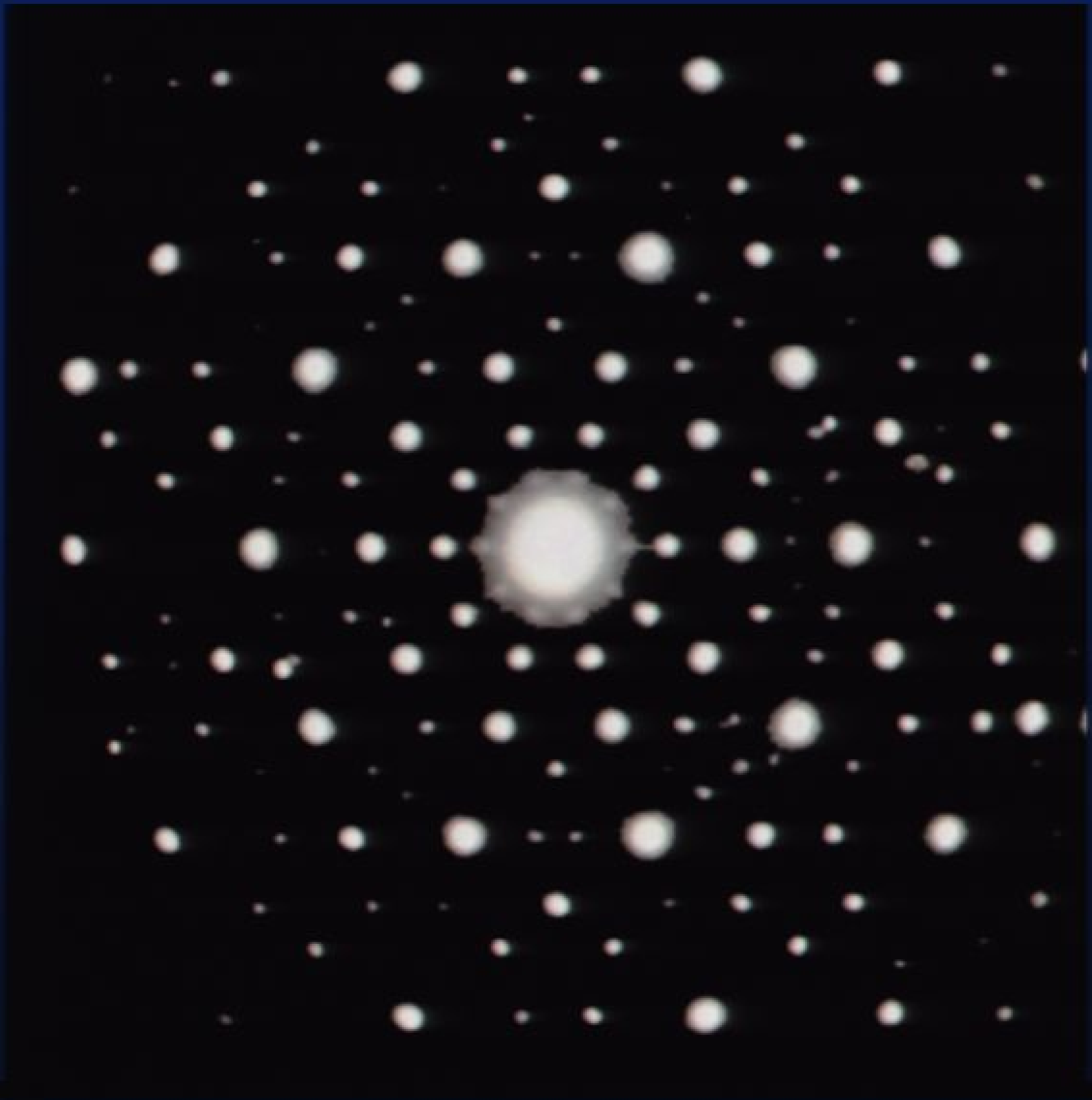
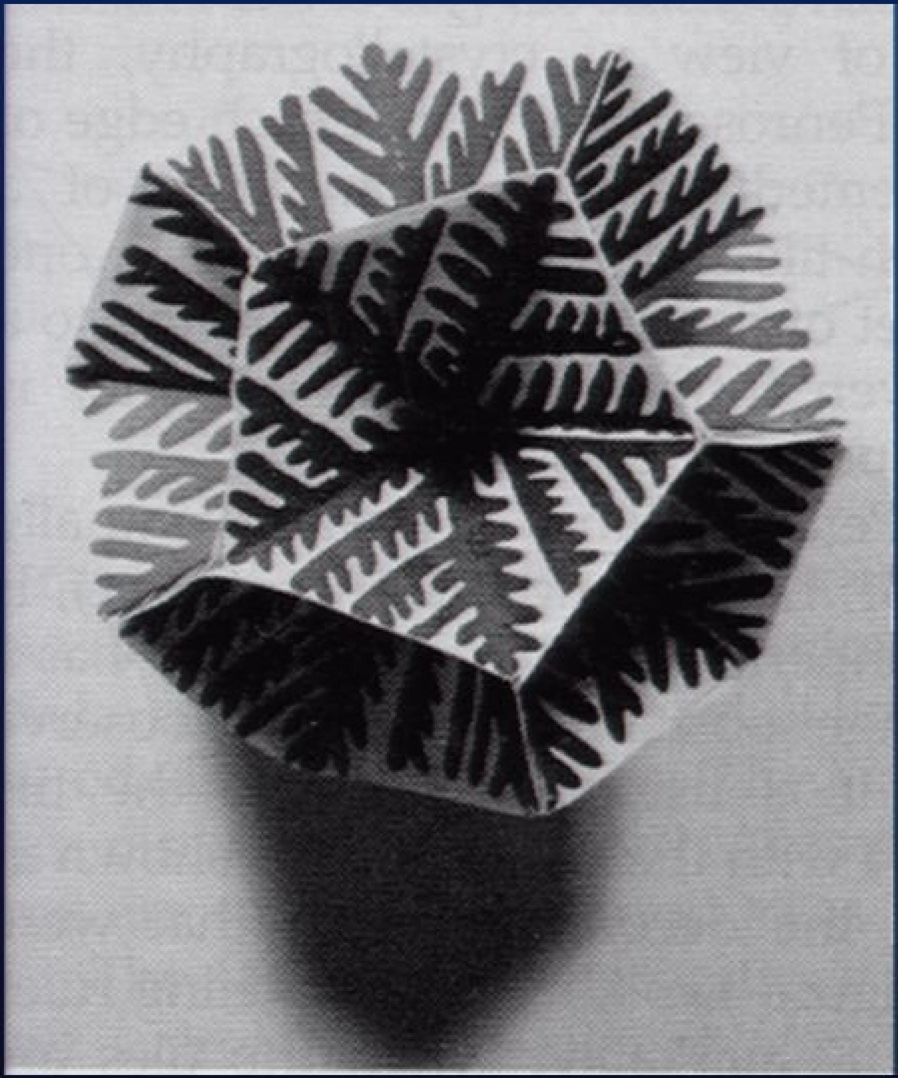
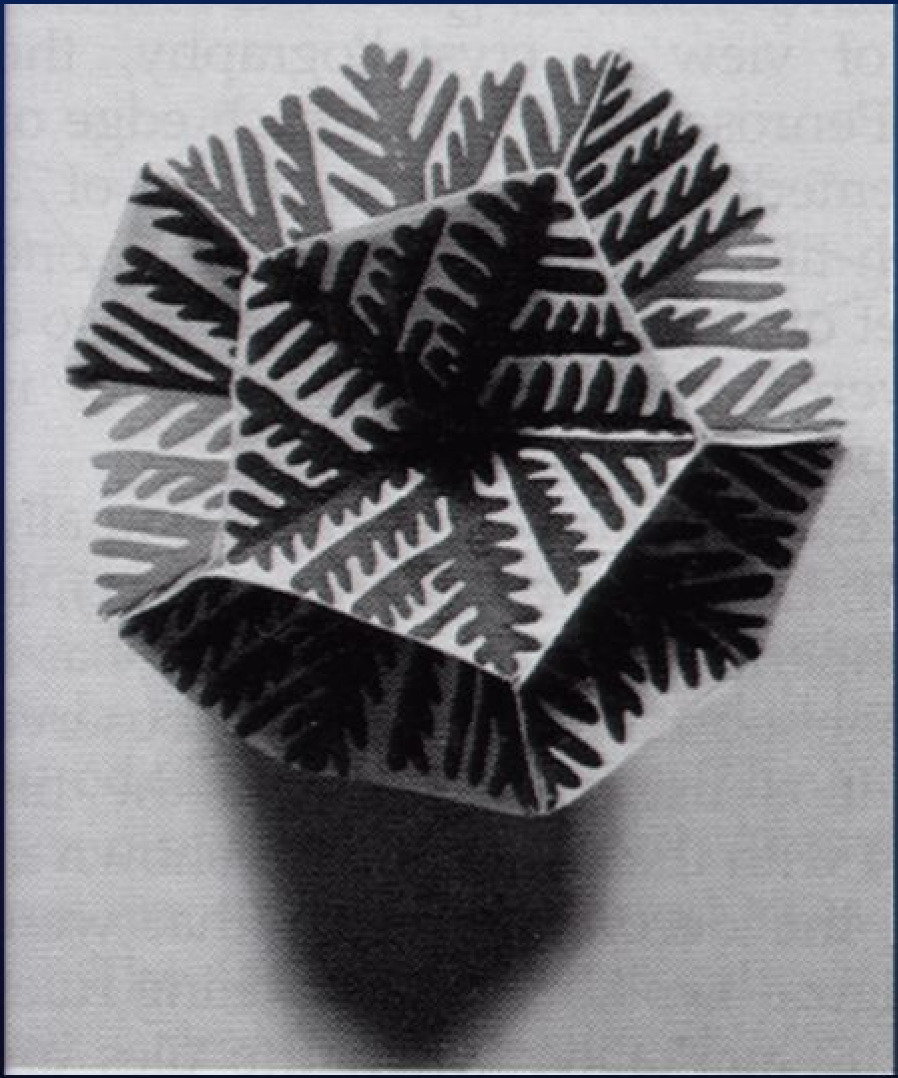
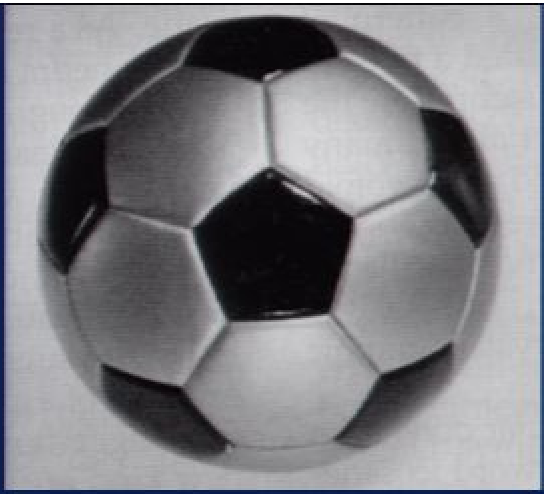
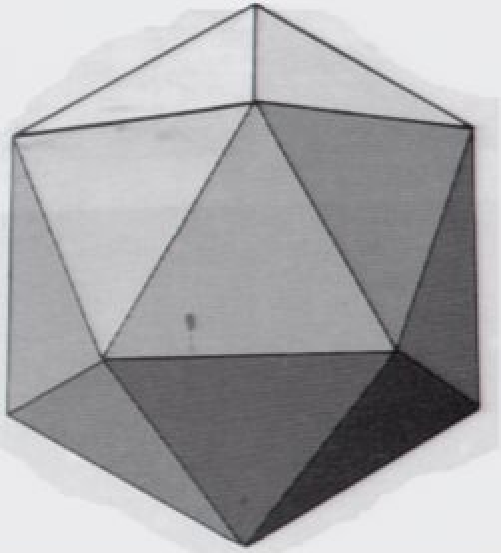


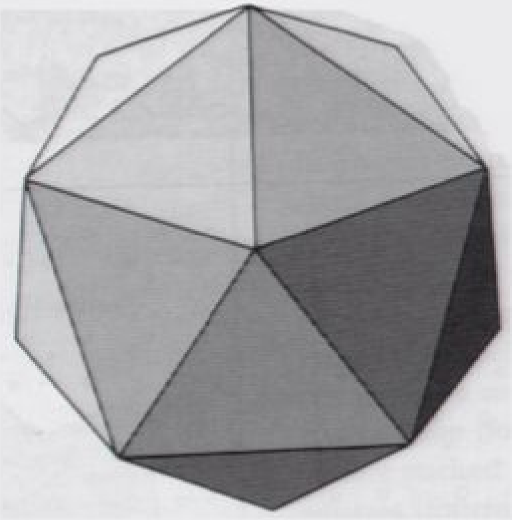




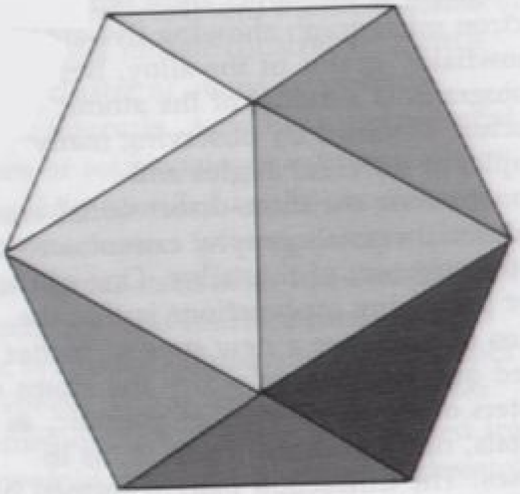




three-fold symmetry axis



five-fold symmetry axis



two-fold symmetry axis

QUASICRYSTALS

- Orderly arrangement
- Rotational Symmetry
- Structure can be reduced to repeating units

D. Levine and P.J. Steinhardt (1984)

QUASICRYSTALS

- Orderly arrangment . . .
  But *QUASIPERIODIC* instead of *PERIODIC*
- Rotational Symmetry
- Structure can be reduced to repeating units

D. Levine and P.J. Steinhardt (1984)

QUASICRYSTALS

- Orderly arrangment . . .
  But *QUASIPERIODIC* instead of *PERIODIC*

- Rotational Symmetry . . .
  But with *FORBIDDEN* symmetry

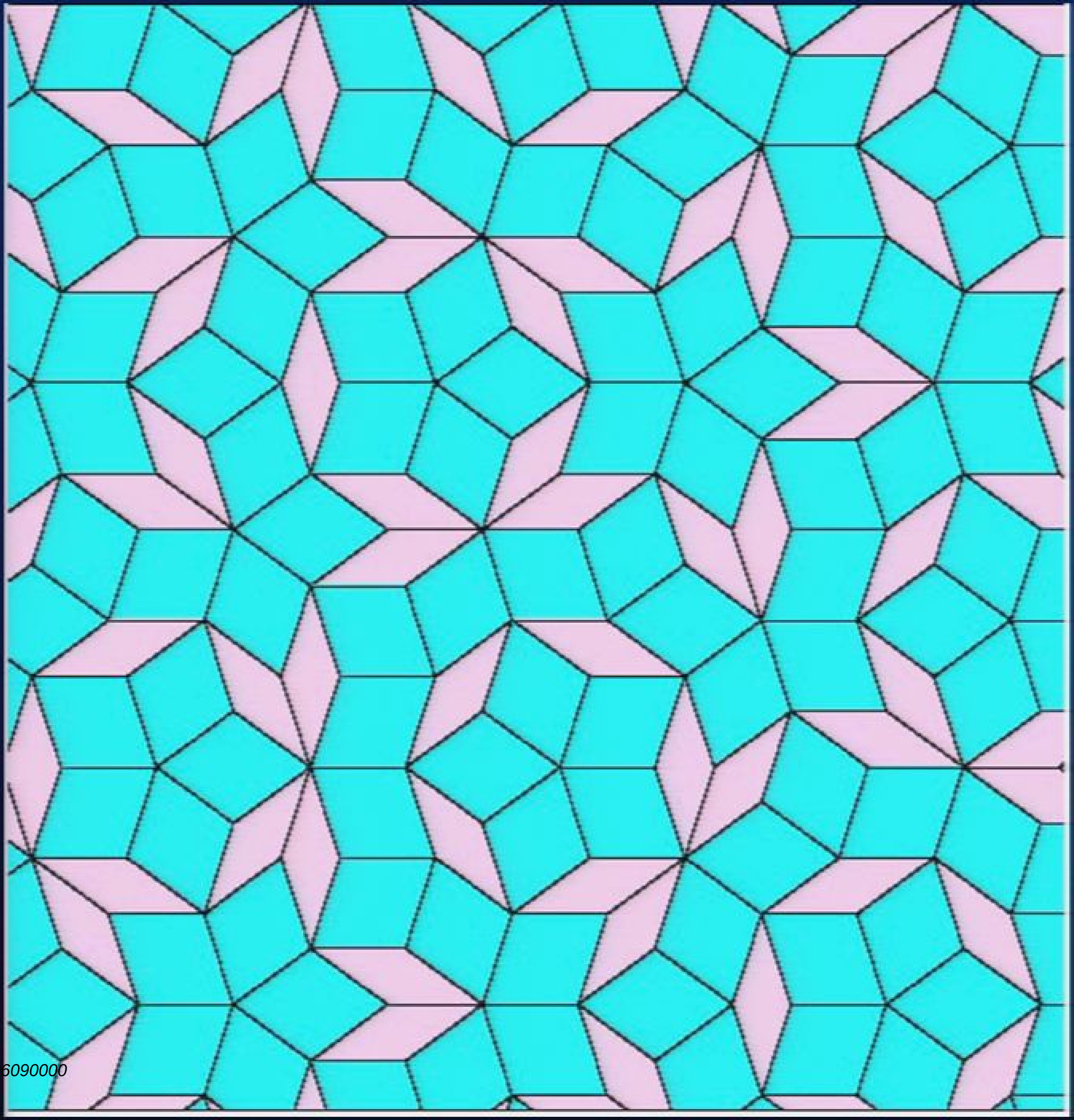
- Structure can be reduced to repeating units

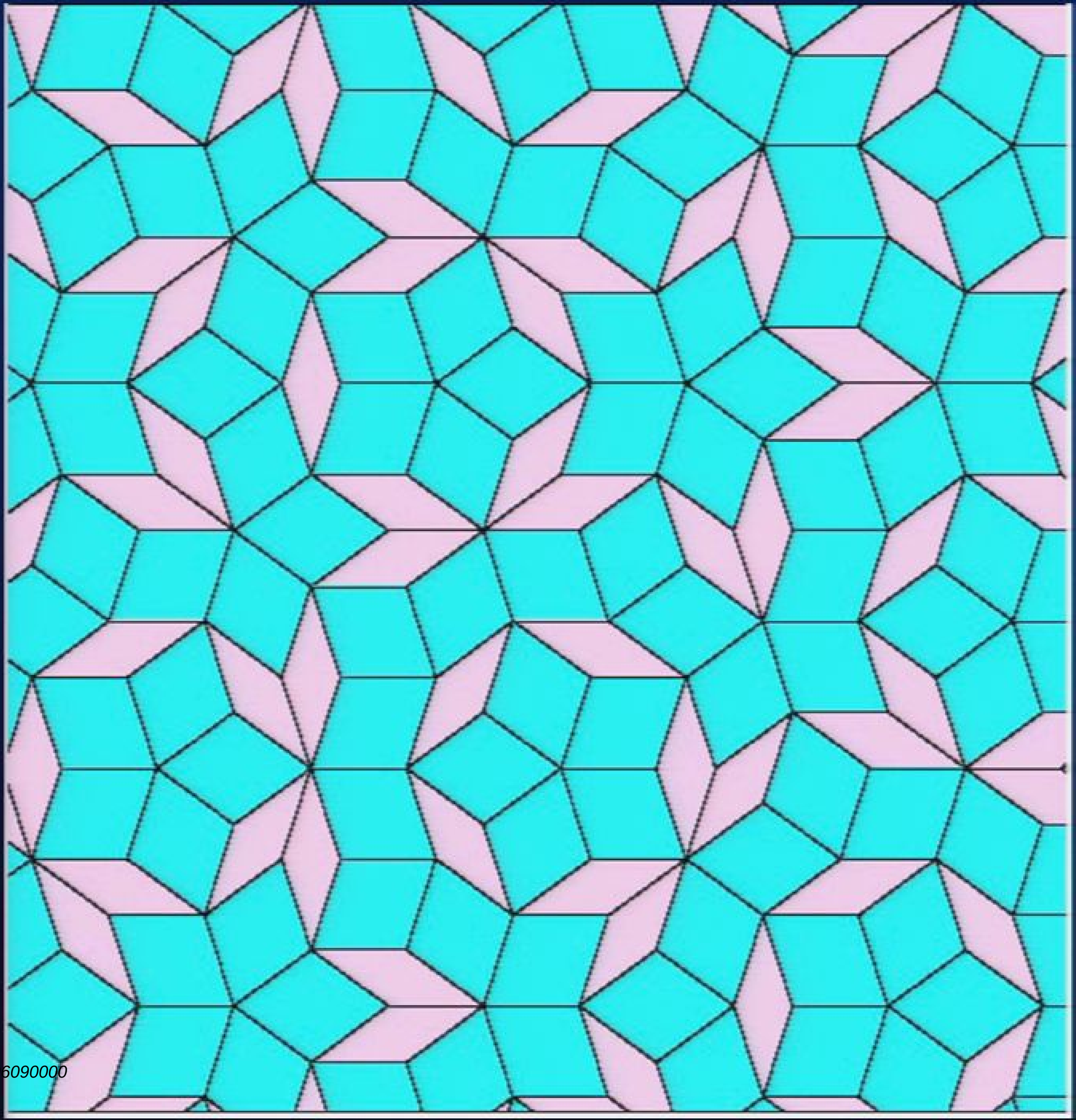
D. Levine and P.J. Steinhardt (1984)

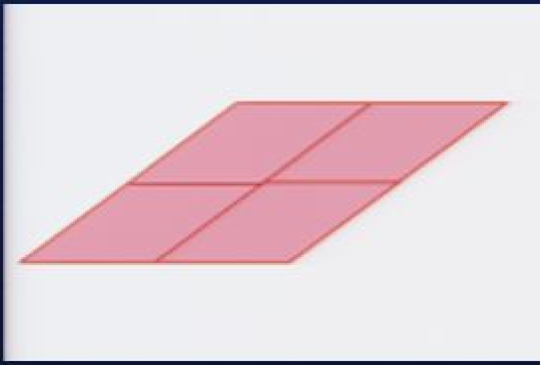
QUASICRYSTALS

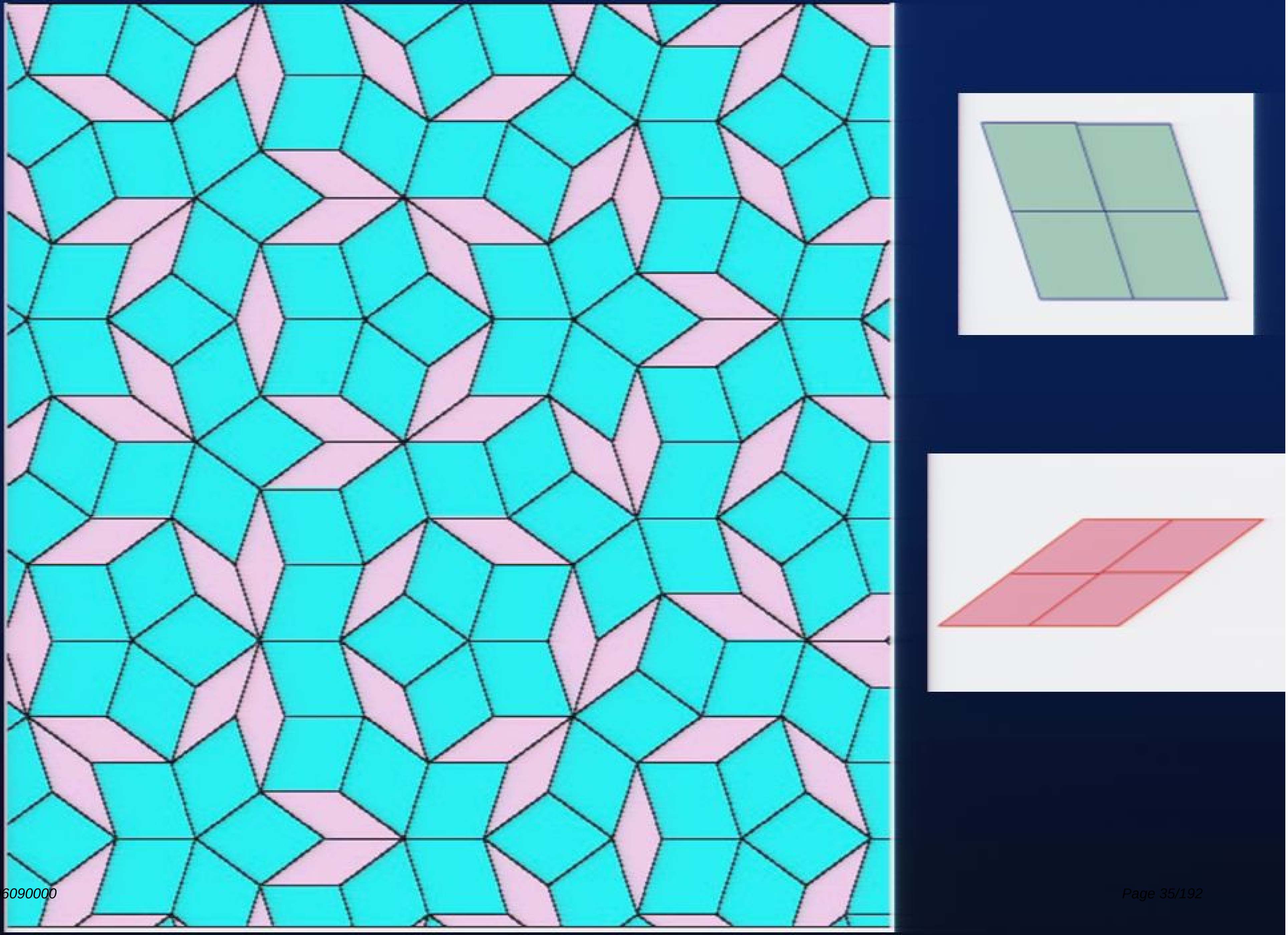
- Orderly arrangmenet . . .
  But *QUASIPERIODIC* instead of *PERIODIC*
- Rotational Symmetry . . .
  But with *FORBIDDEN* symmetry
- Structure can be reduced to a finite number of repeating units

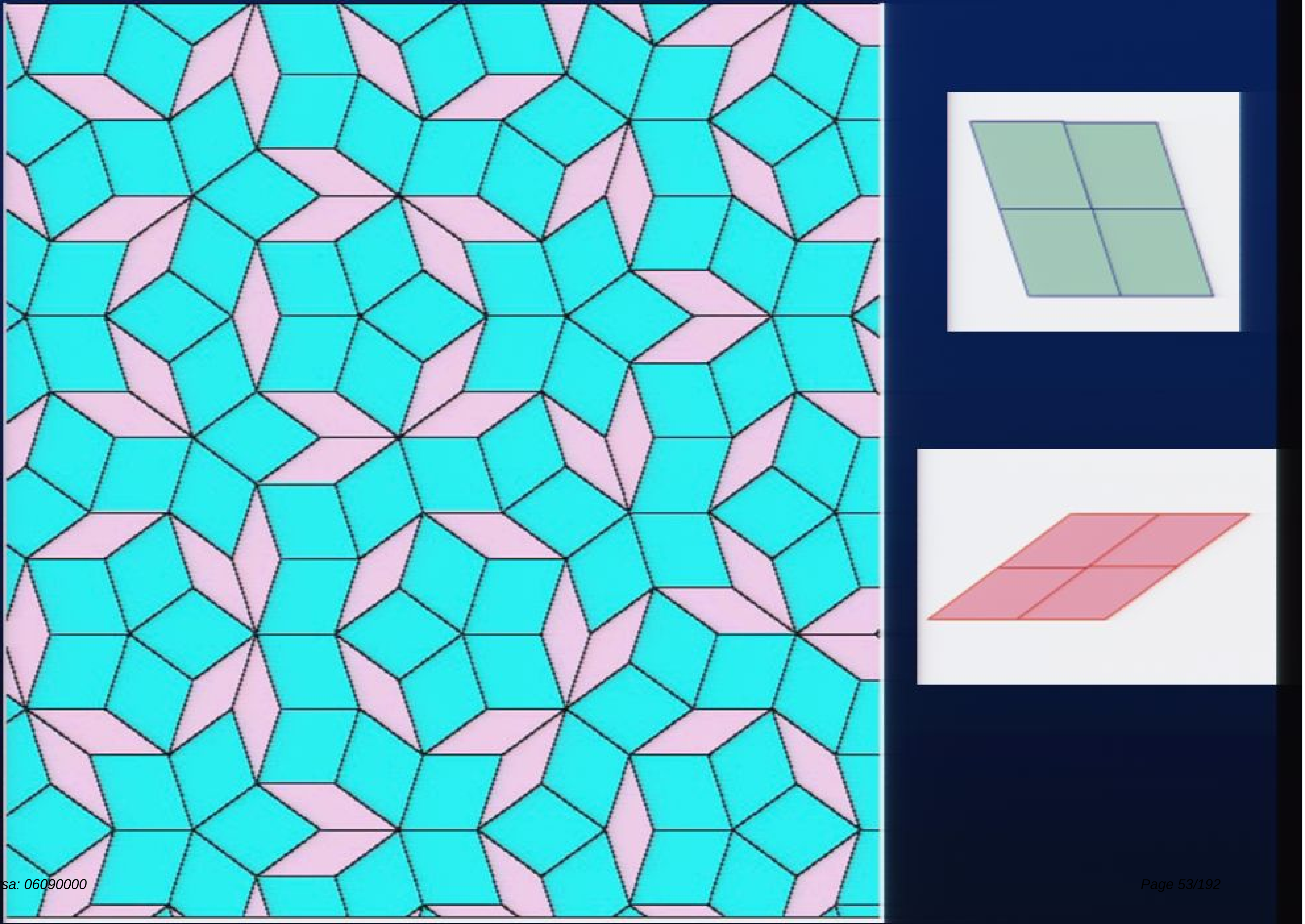
D. Levine and P.J. Steinhardt (1984)

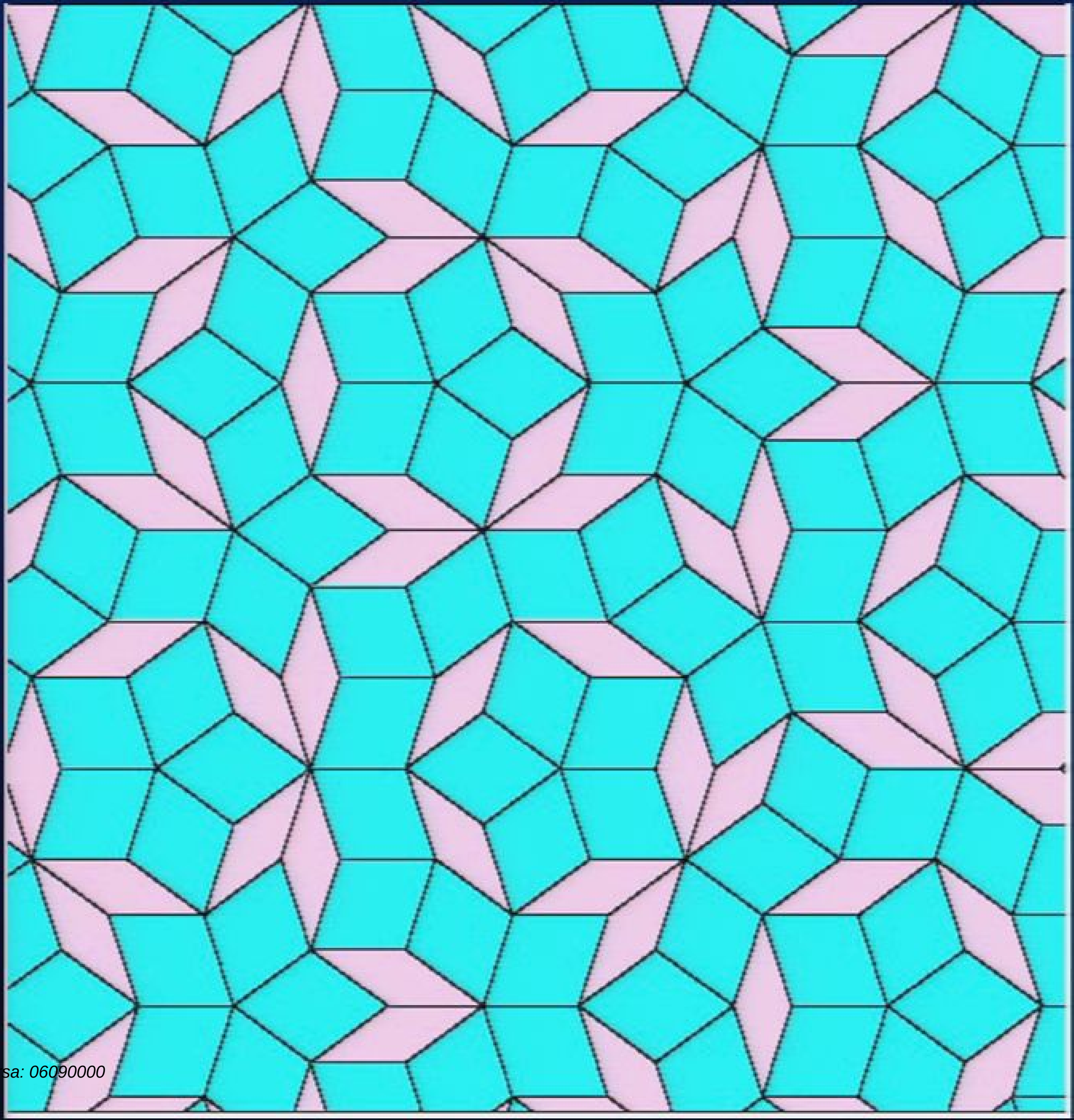


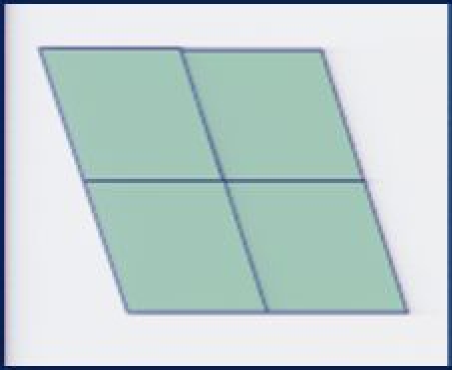


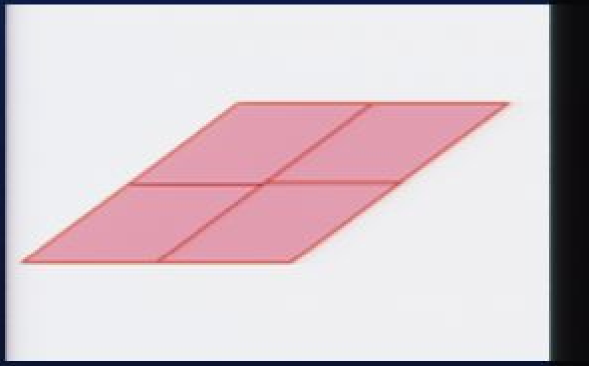


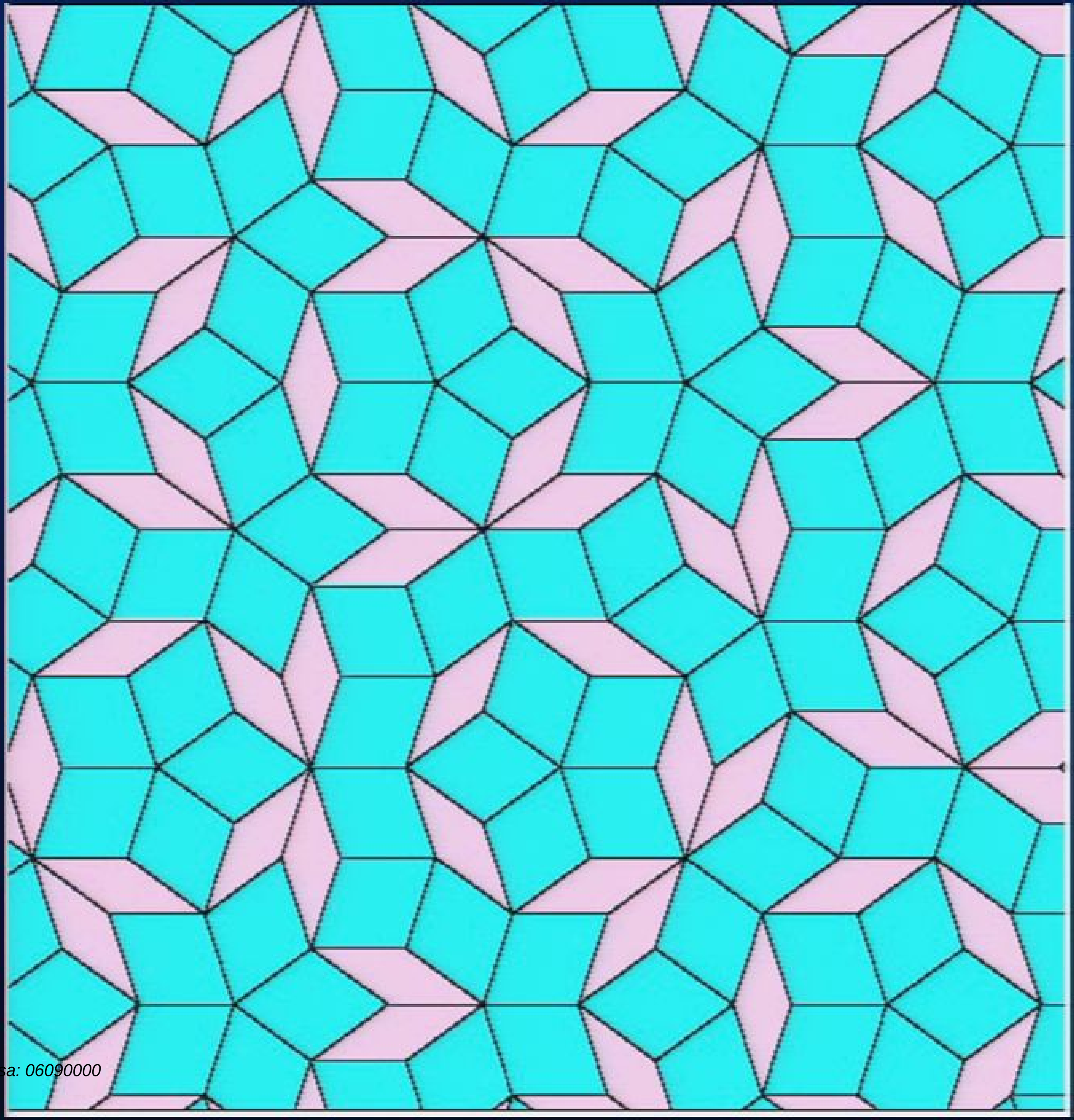


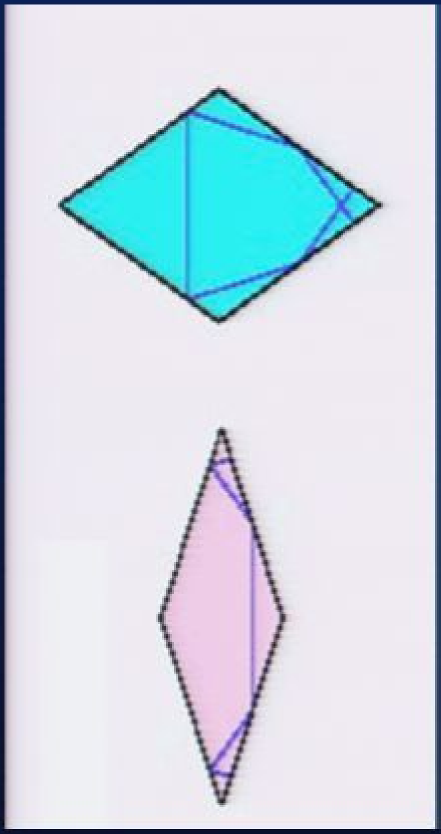


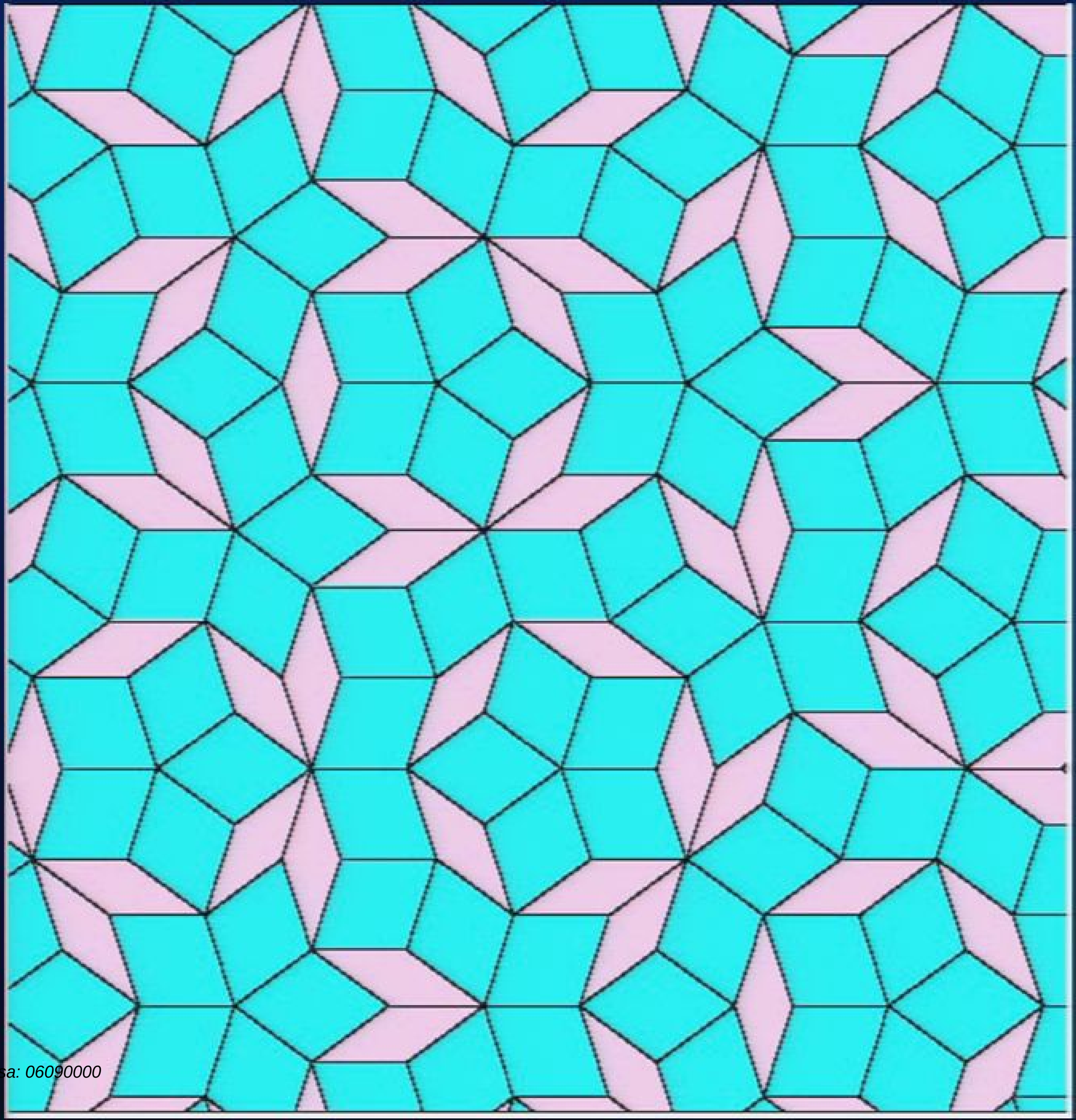


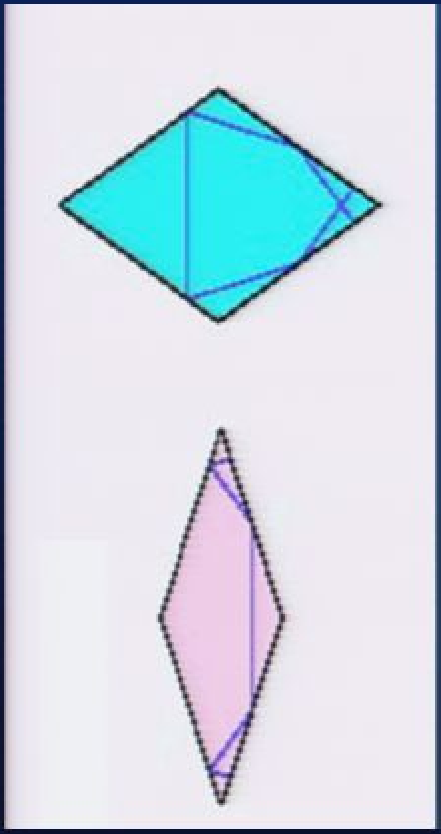


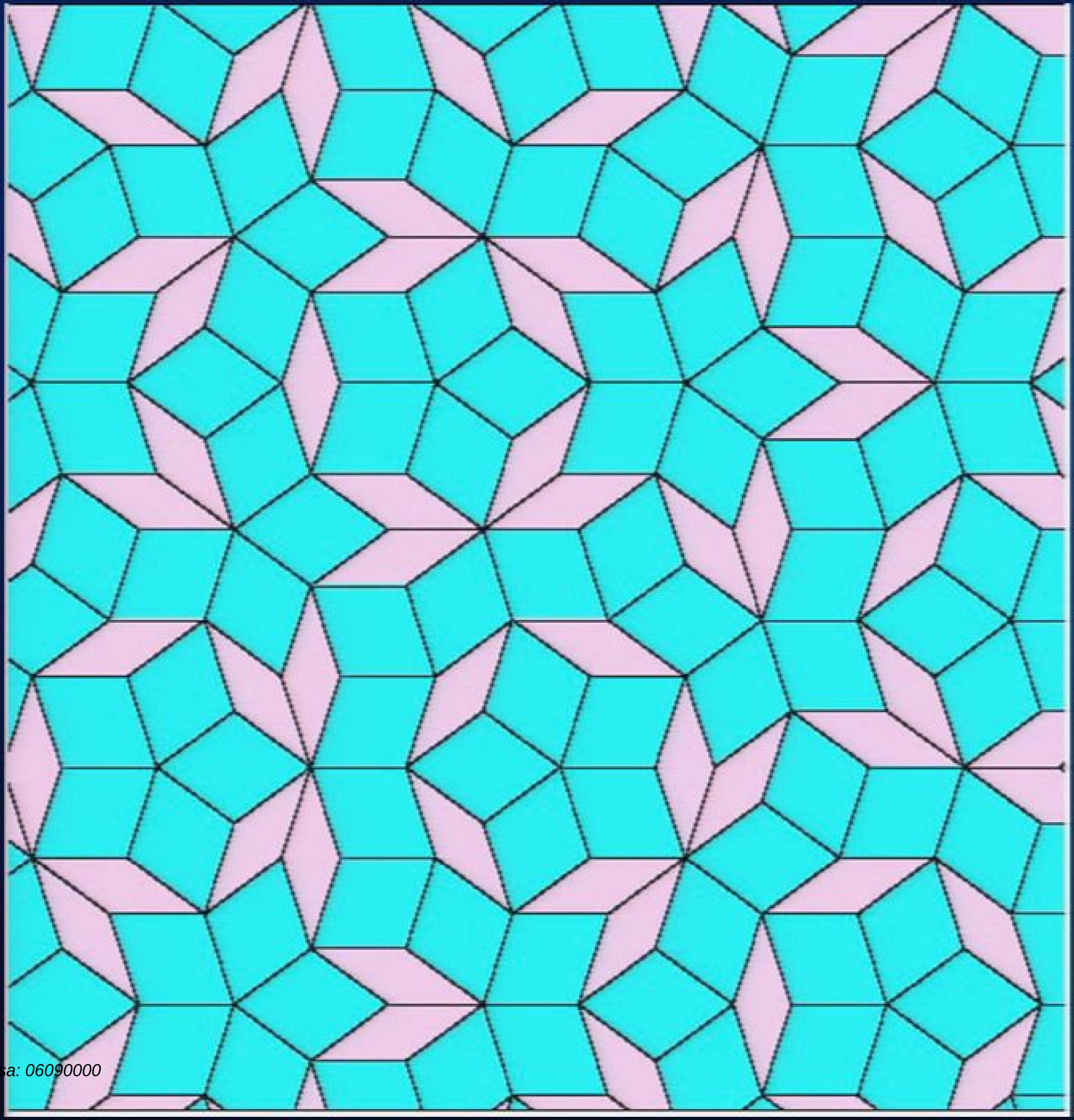


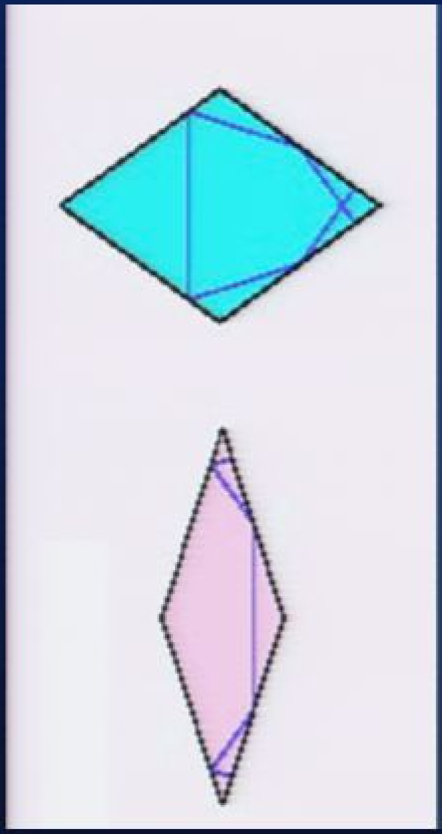


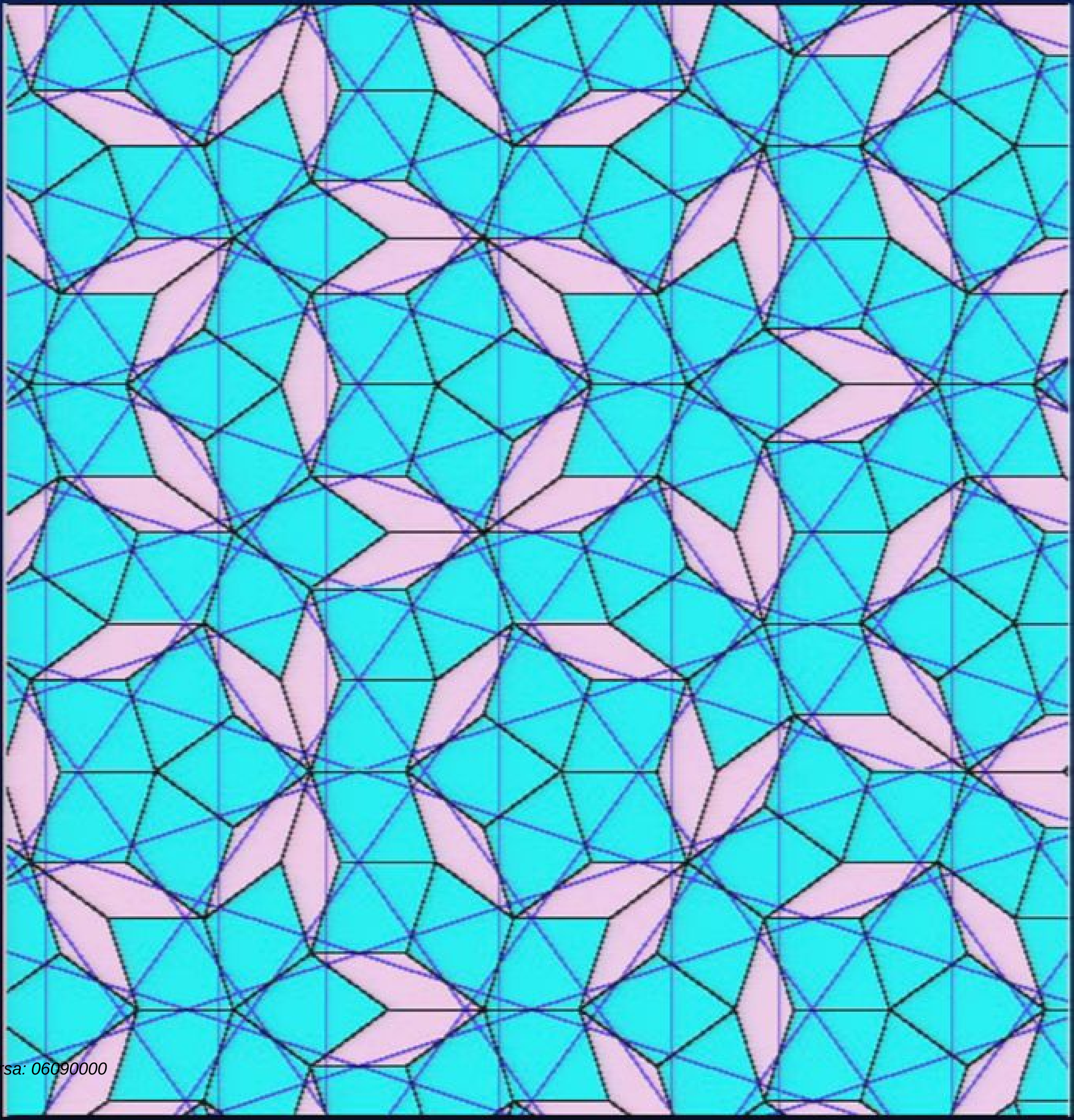


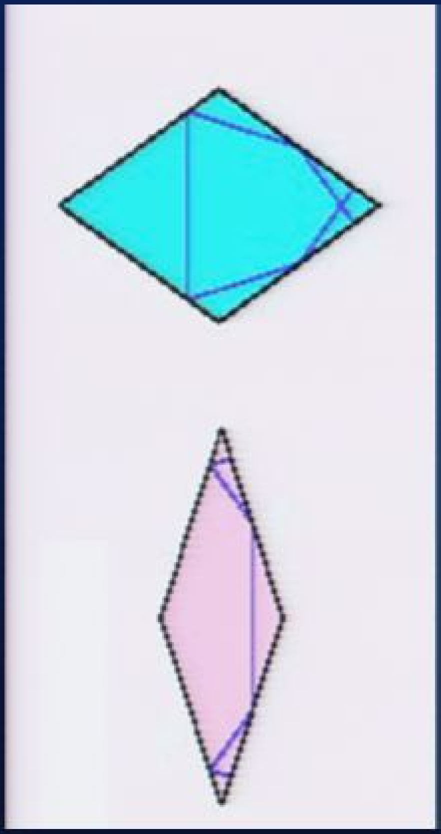


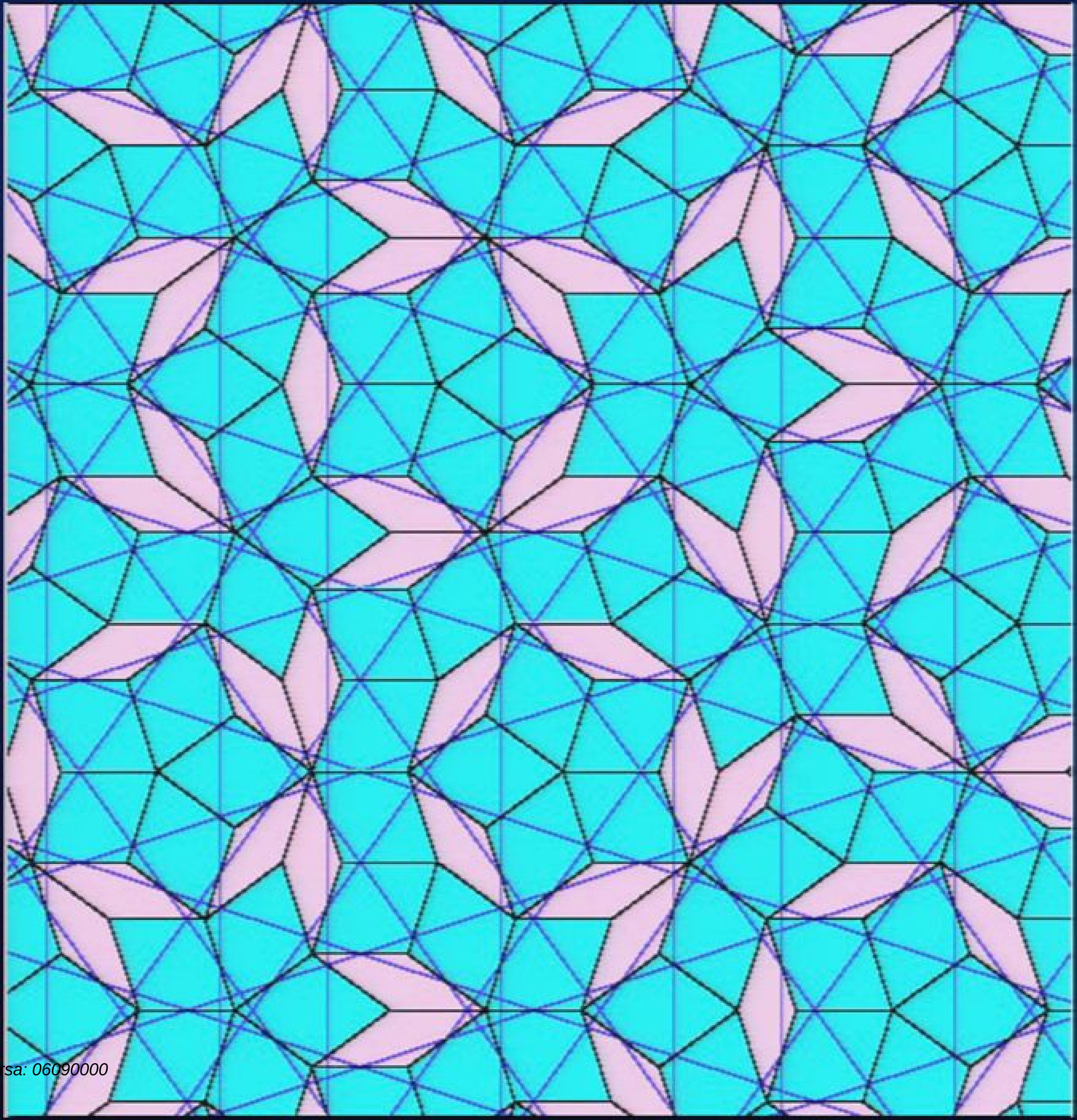


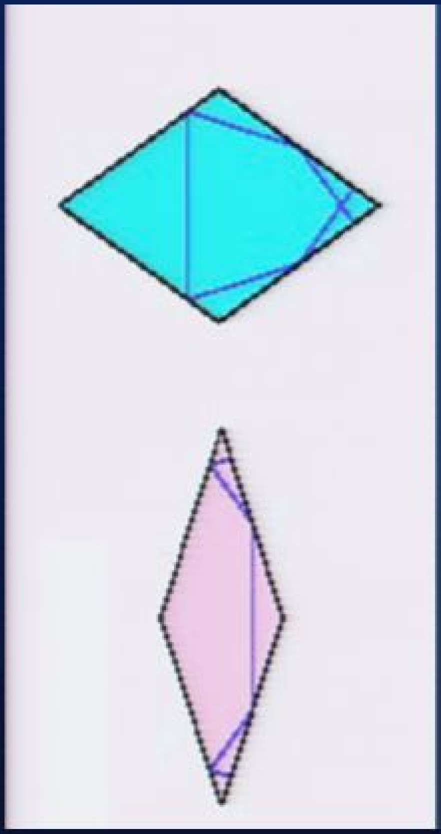


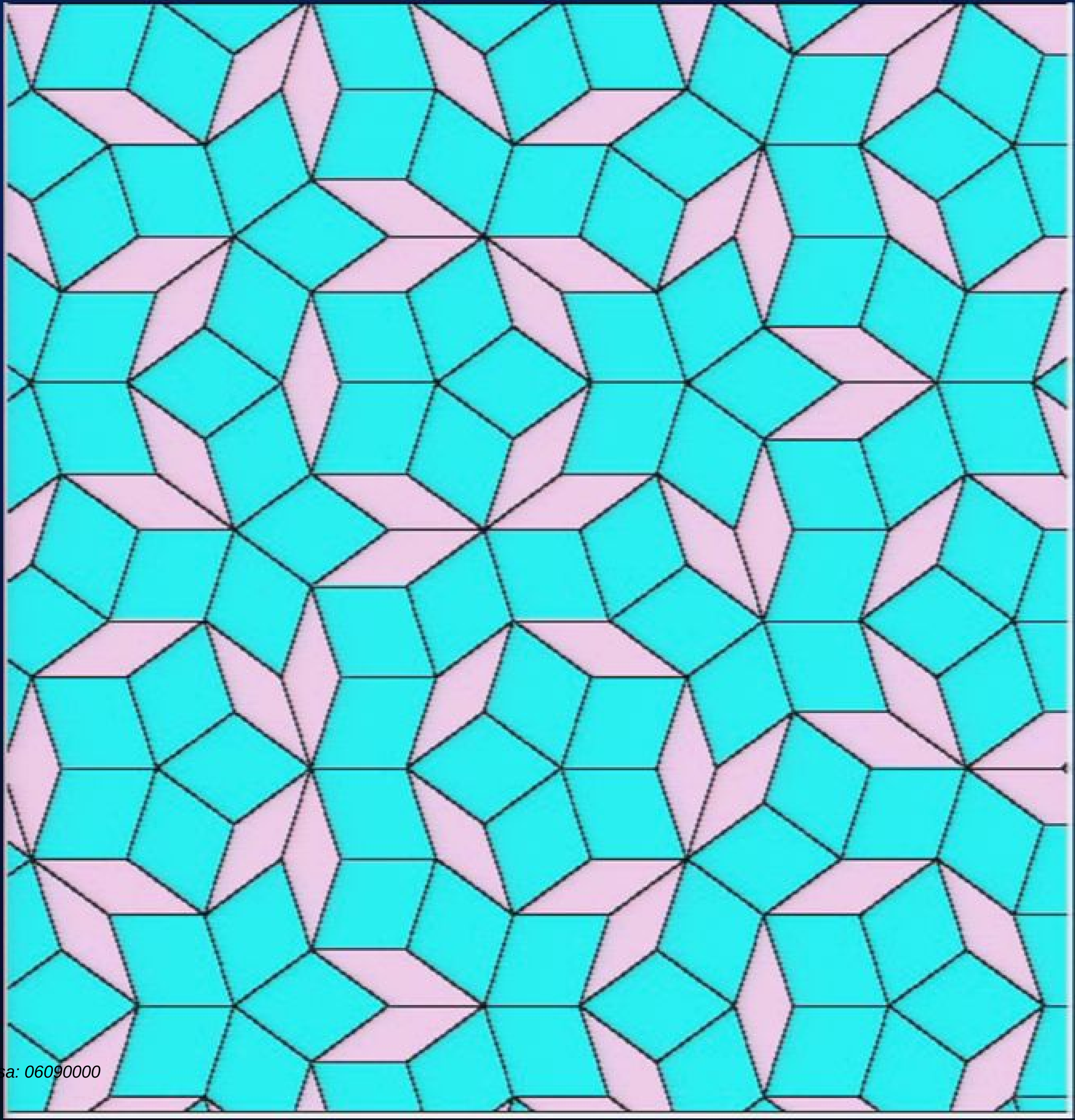


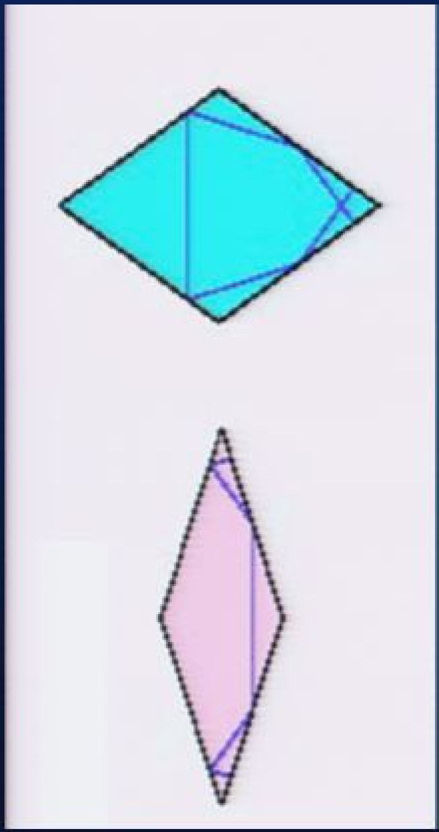


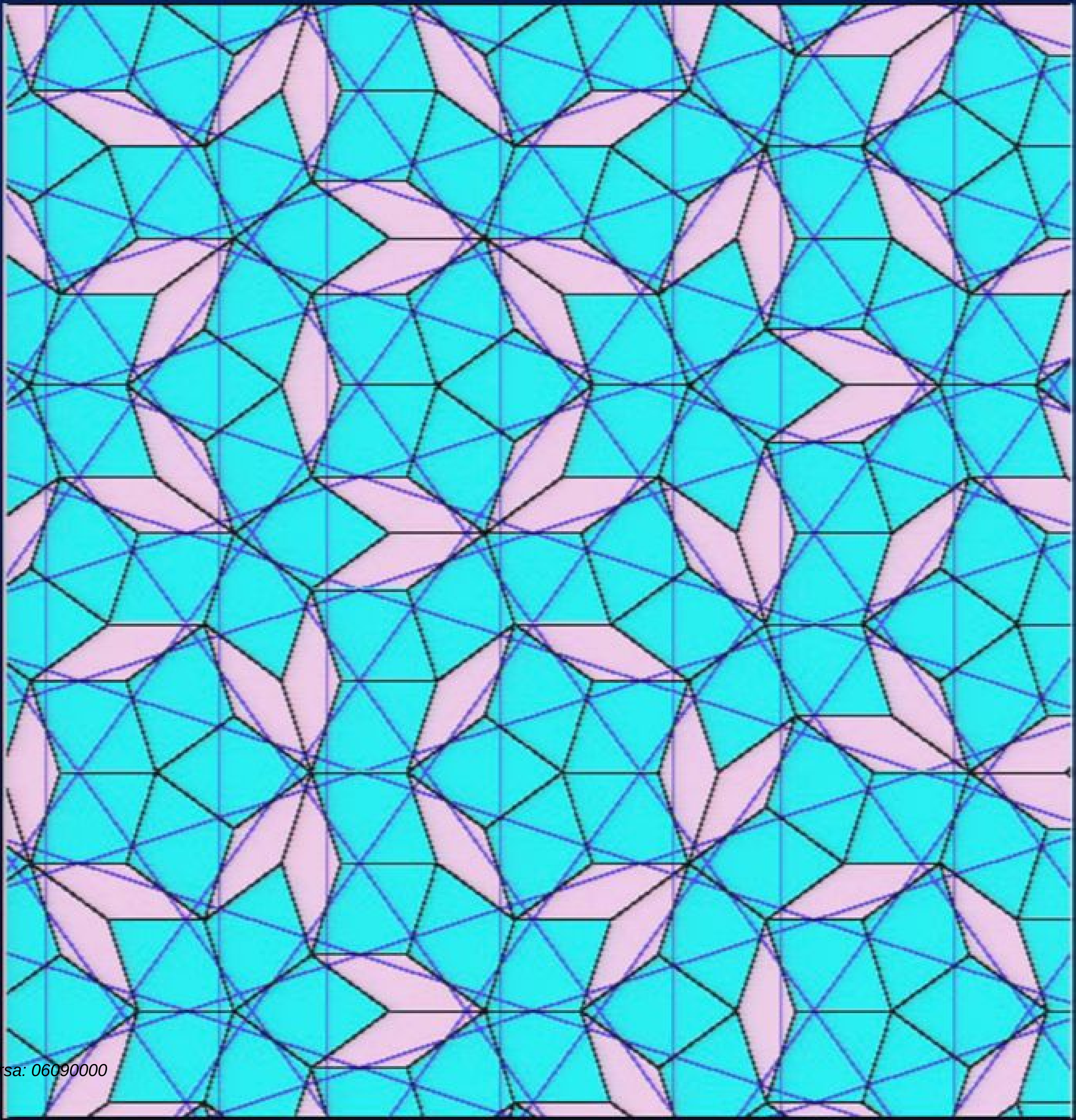


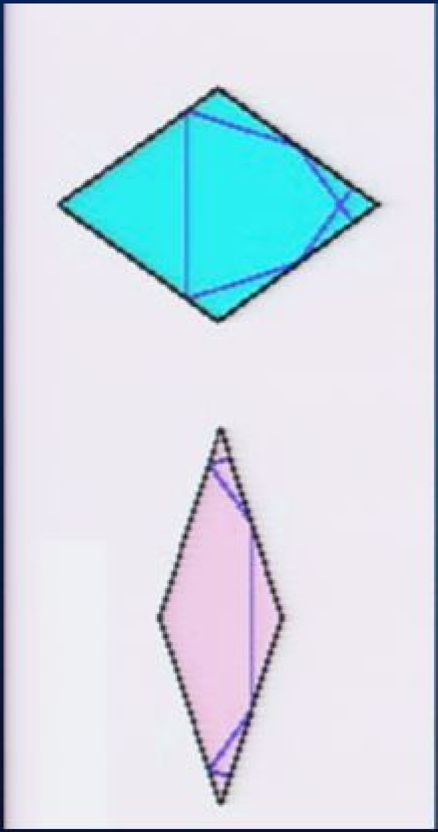


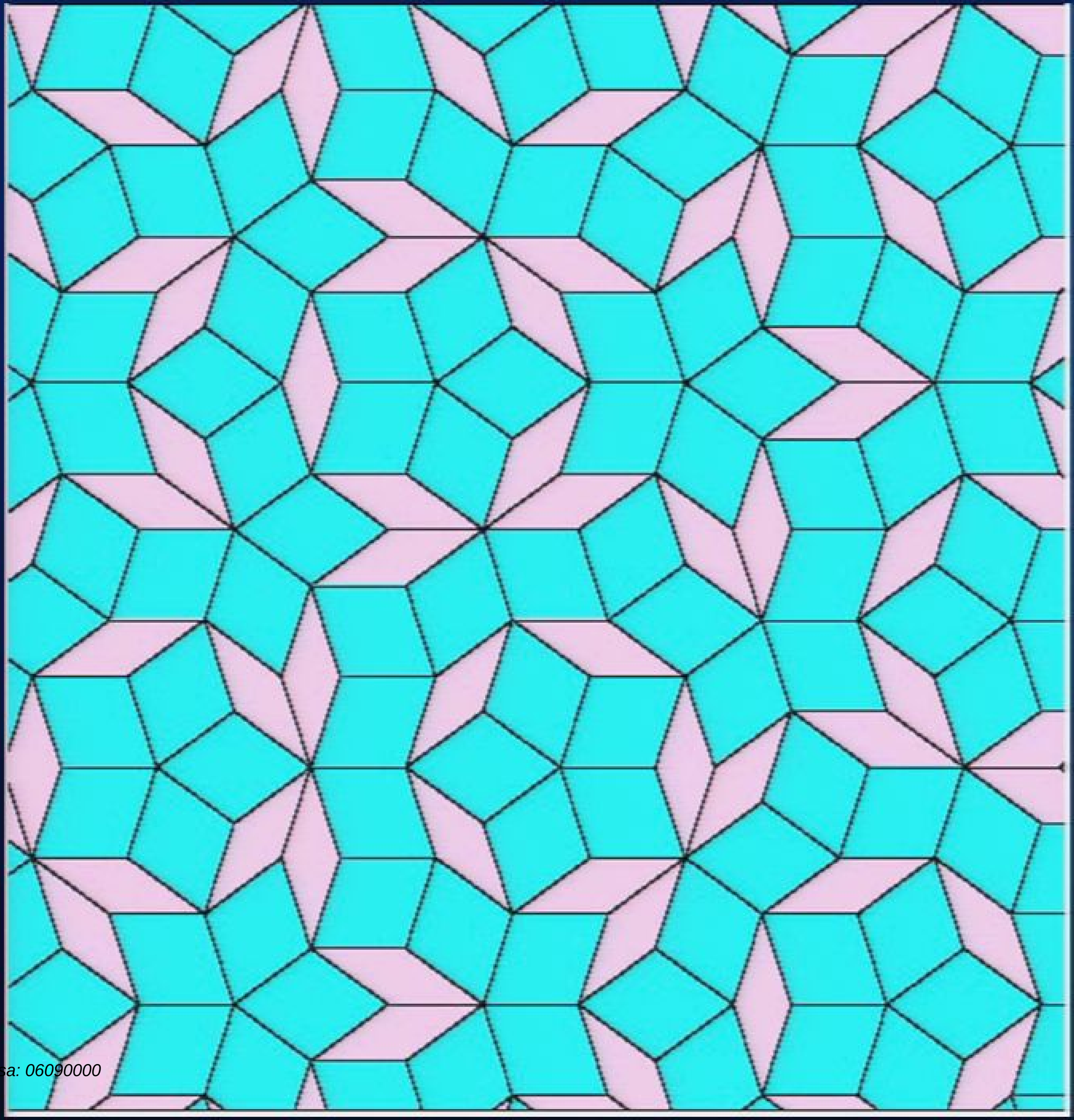


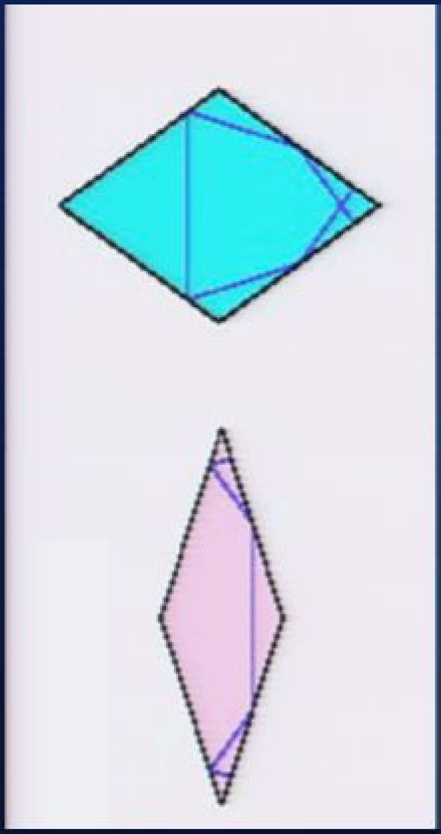


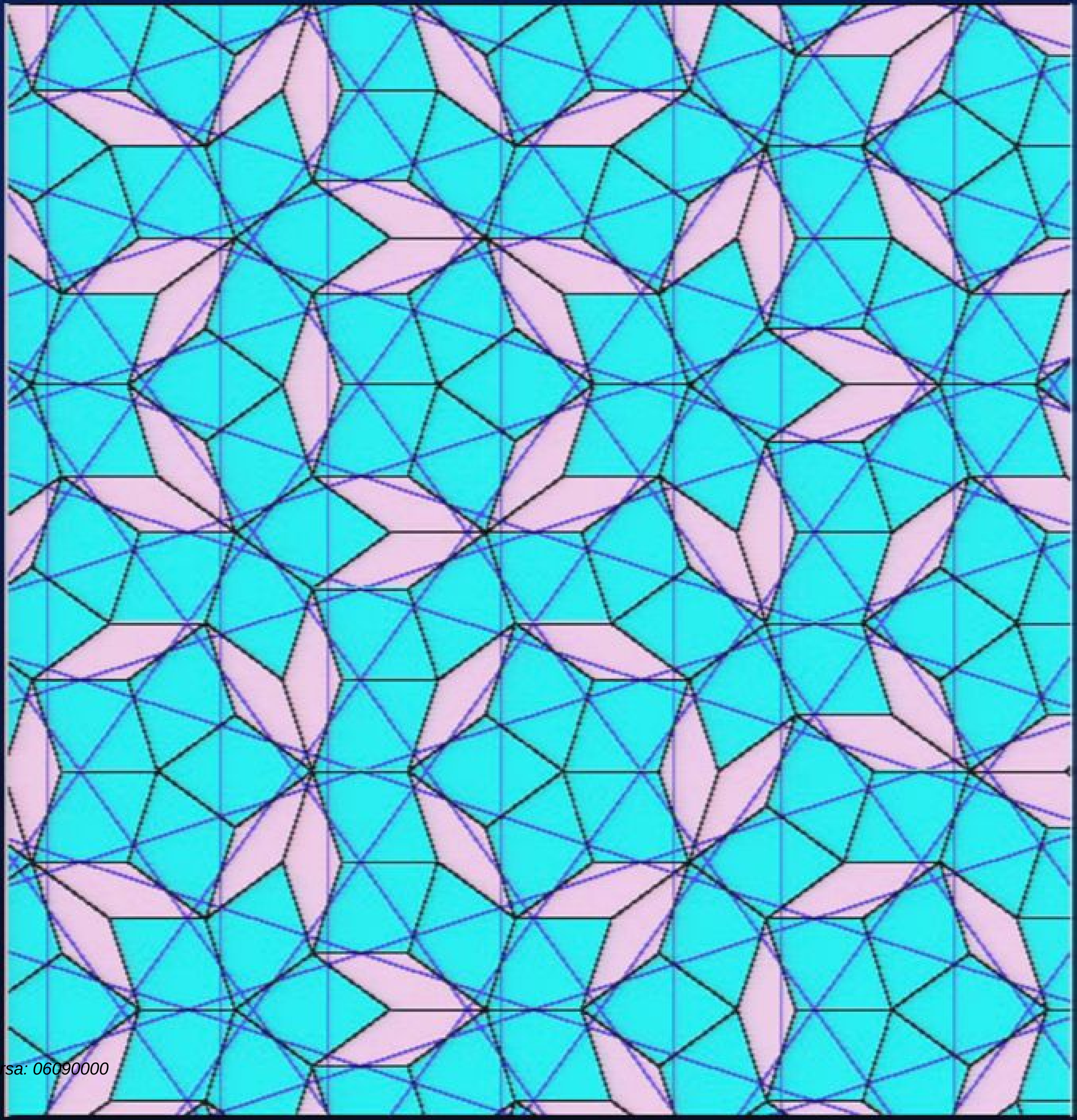


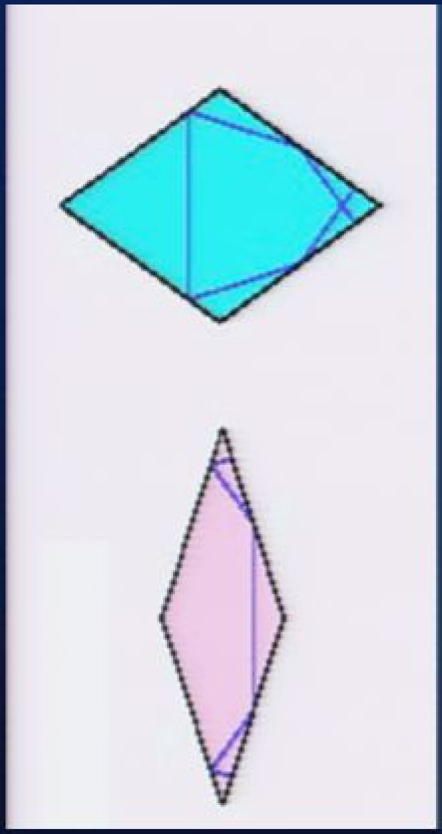


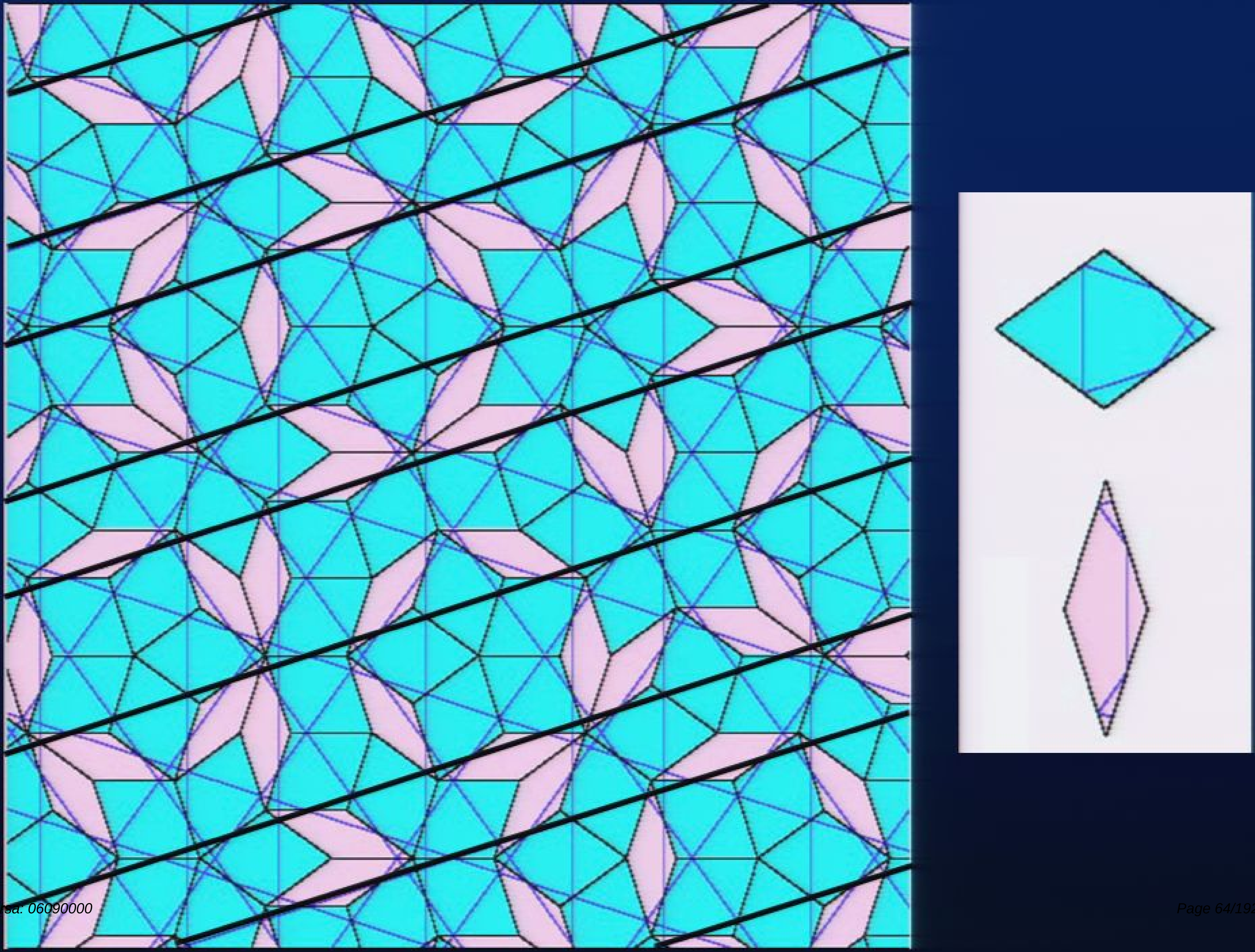


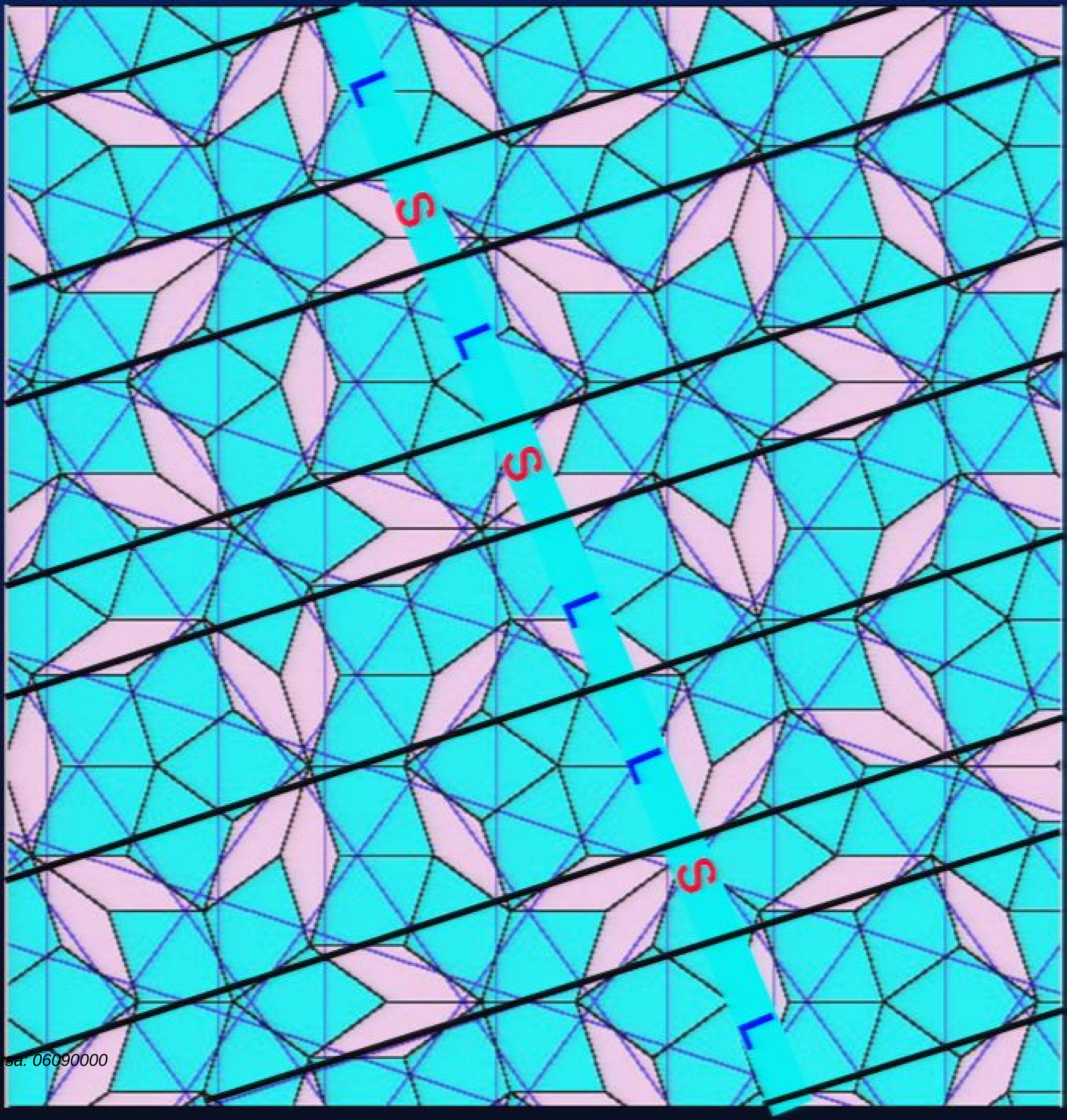








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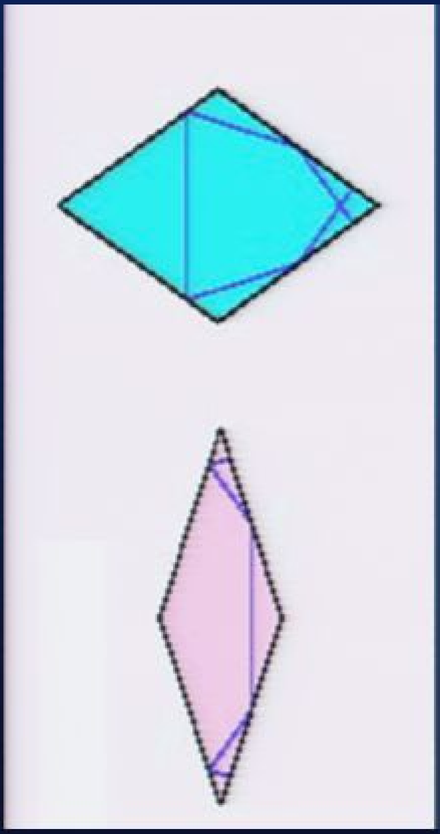
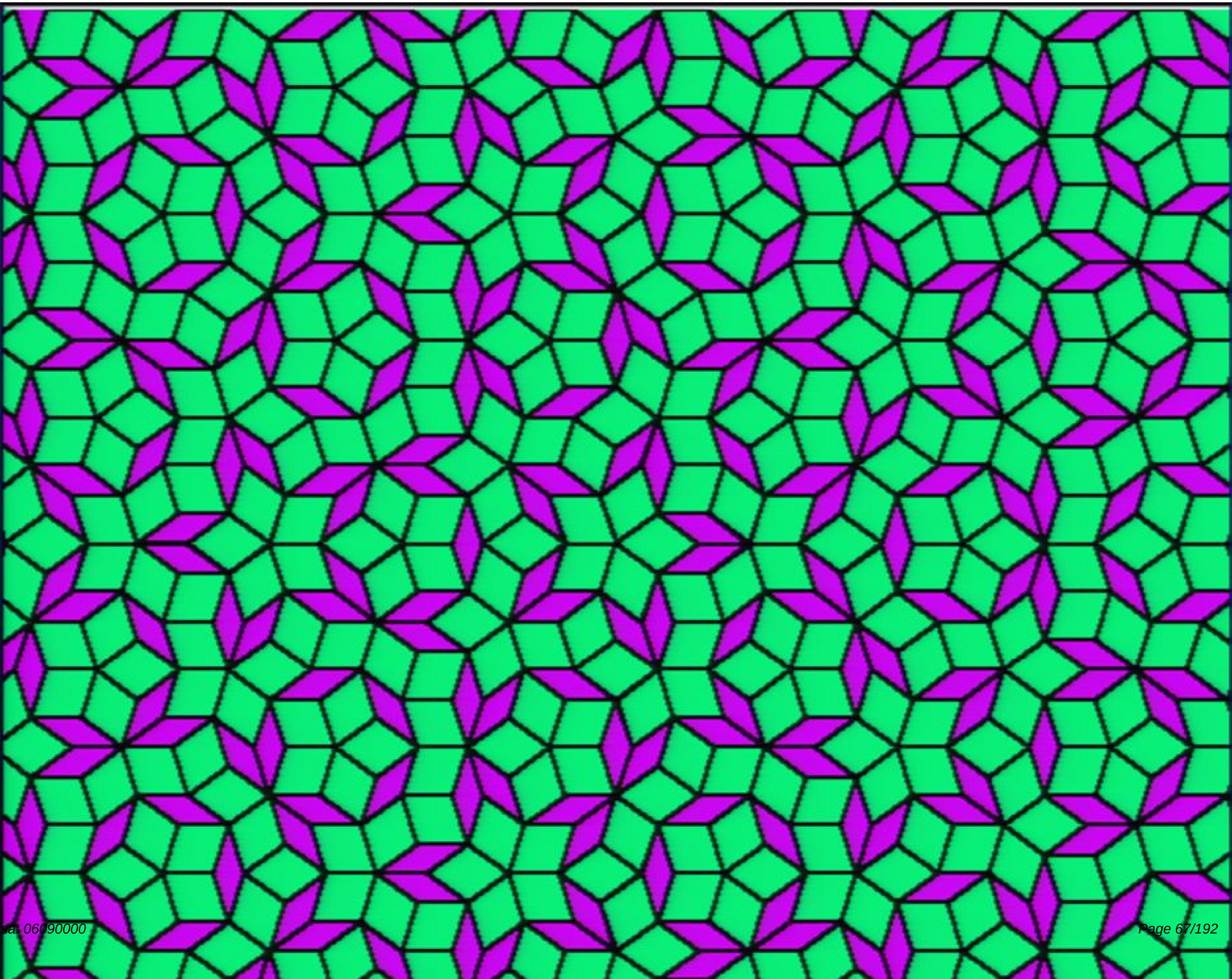
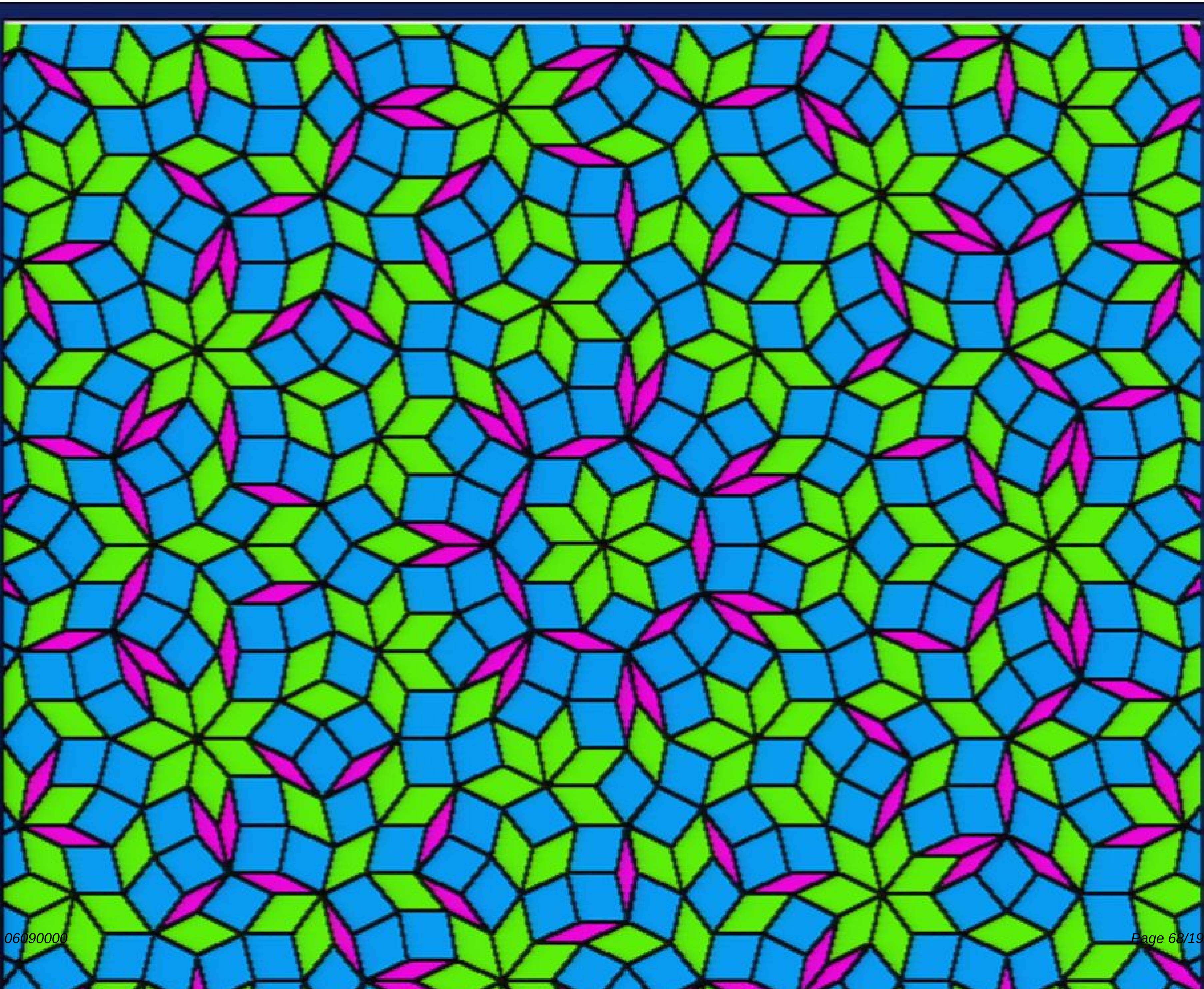
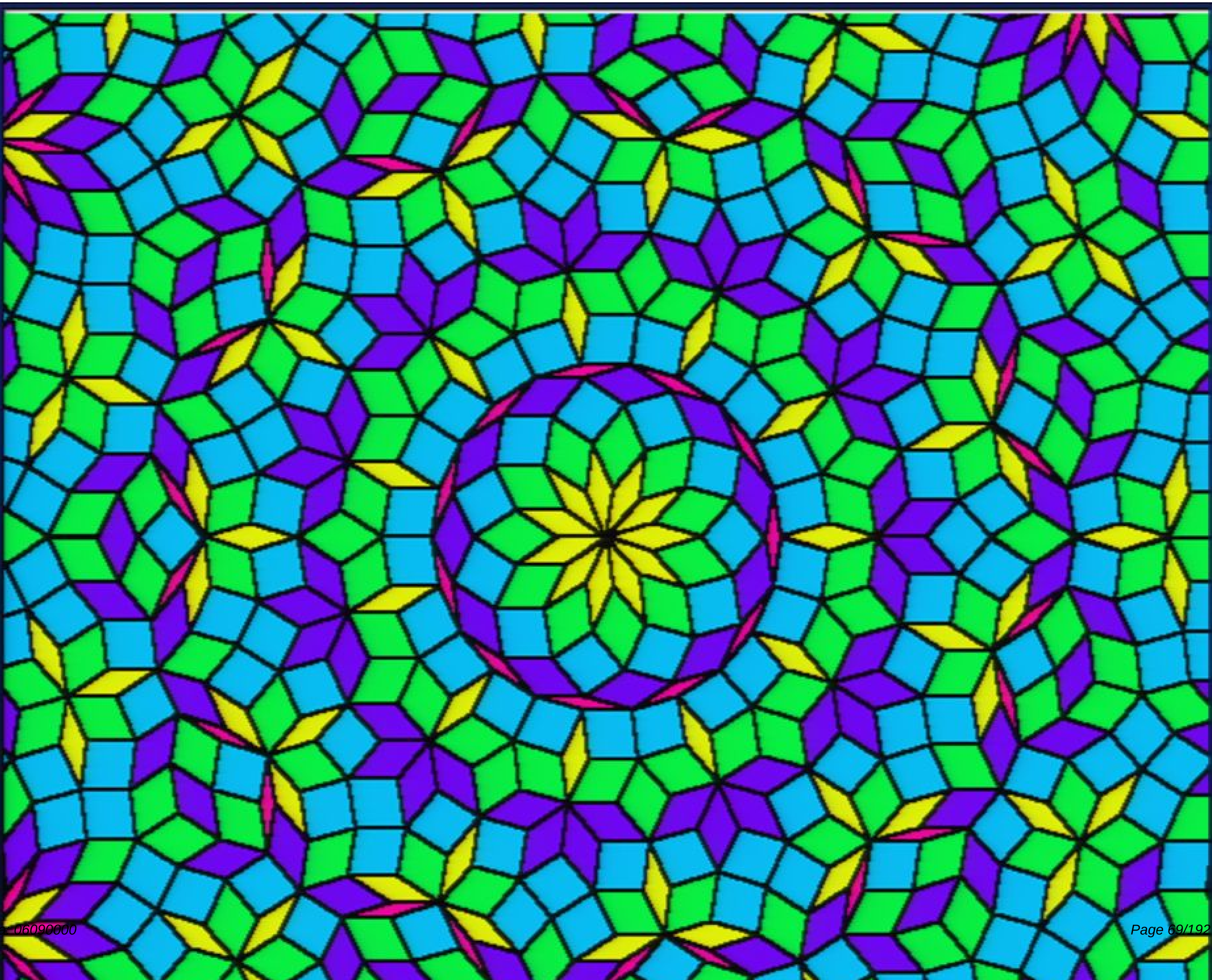


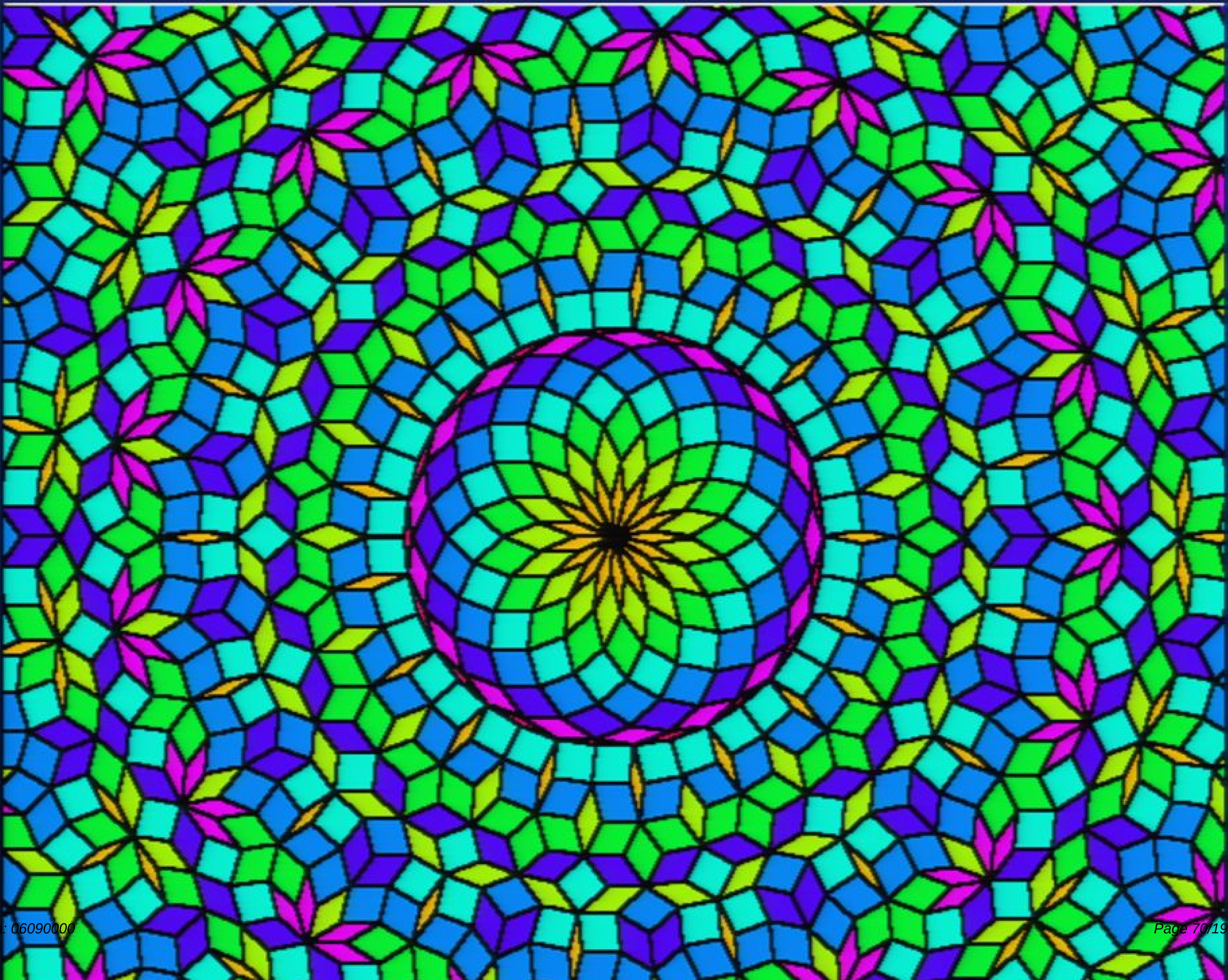
For Quasicrystals, Any Symmetry is Possible

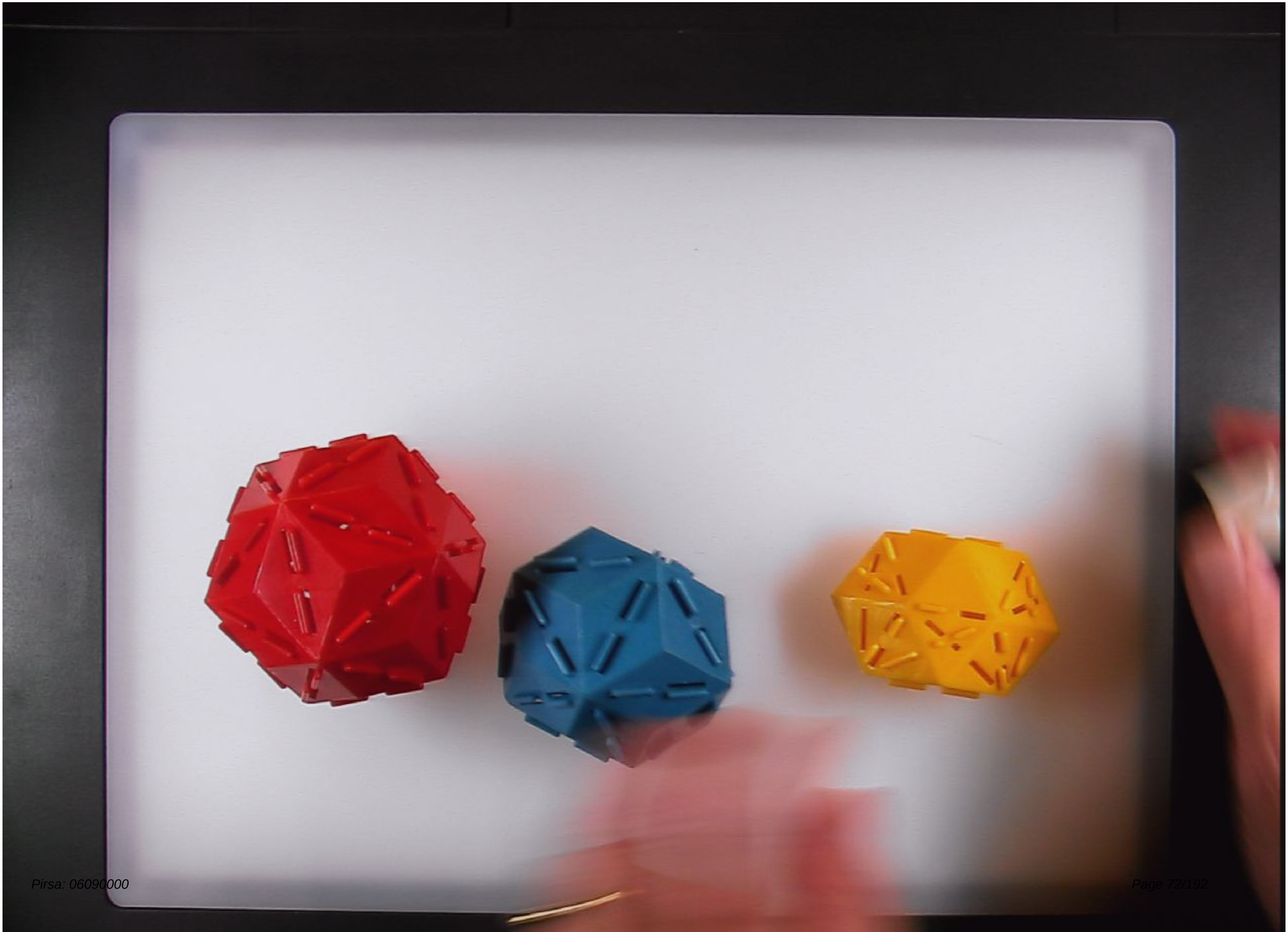
J. Socolar, D. Levine, and PJS (1985)

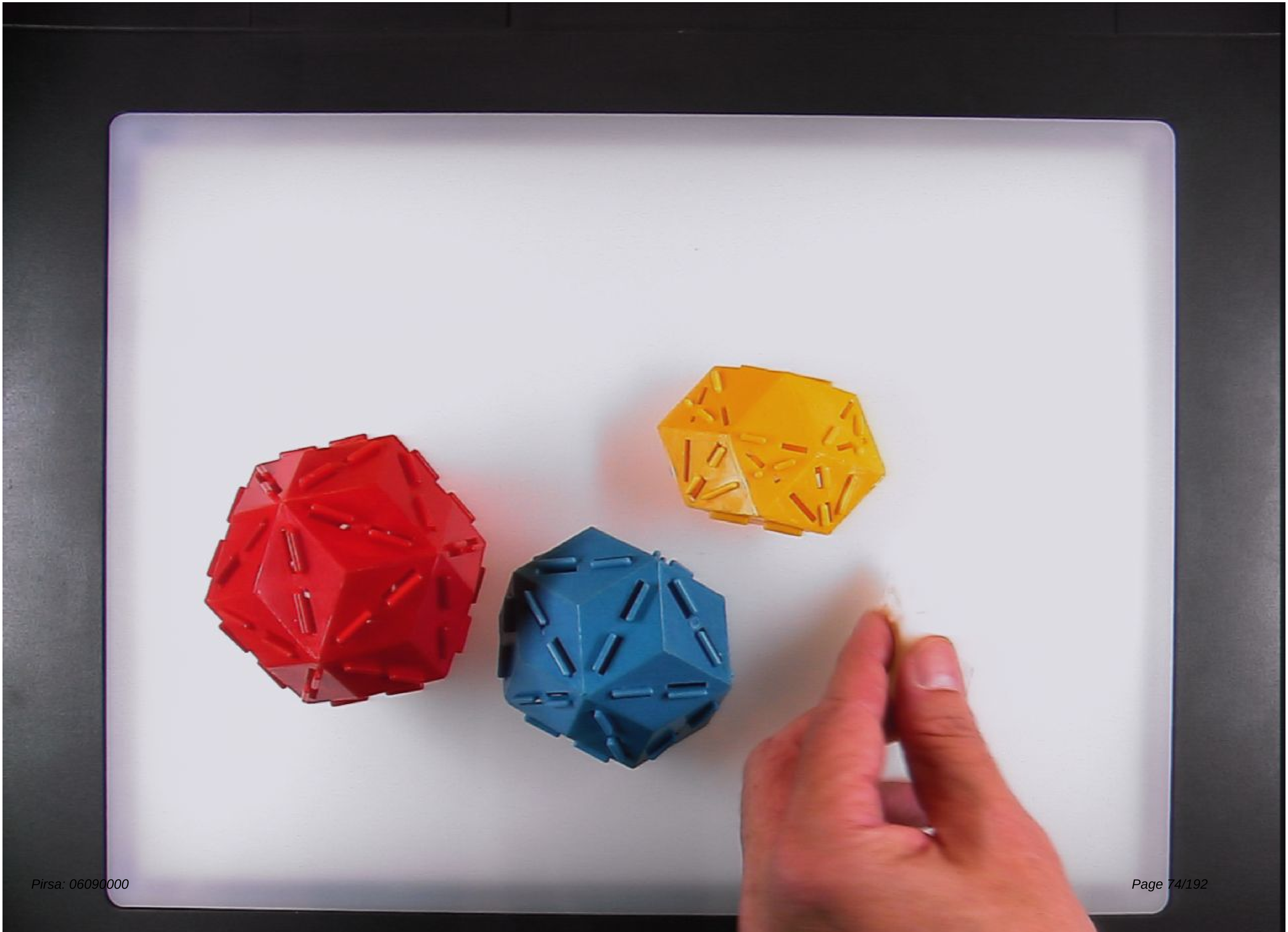


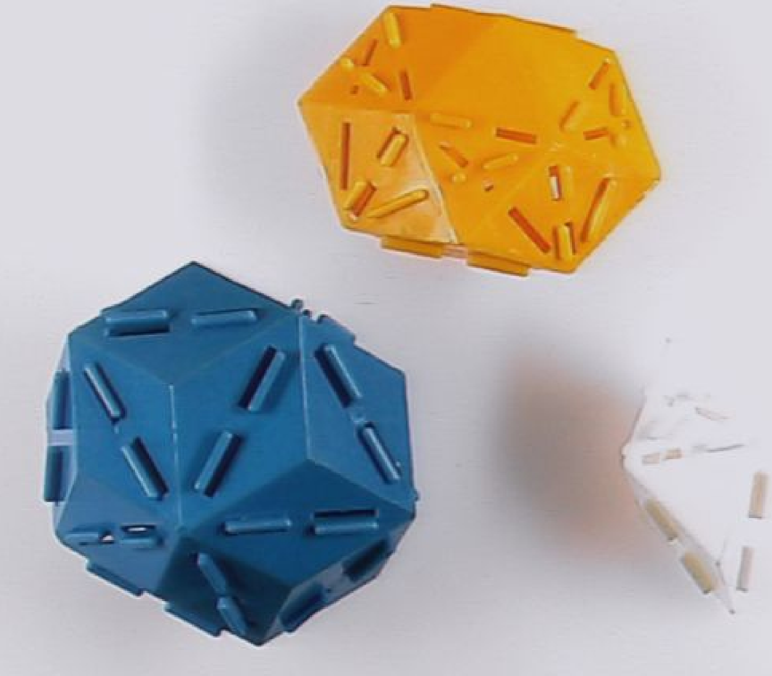


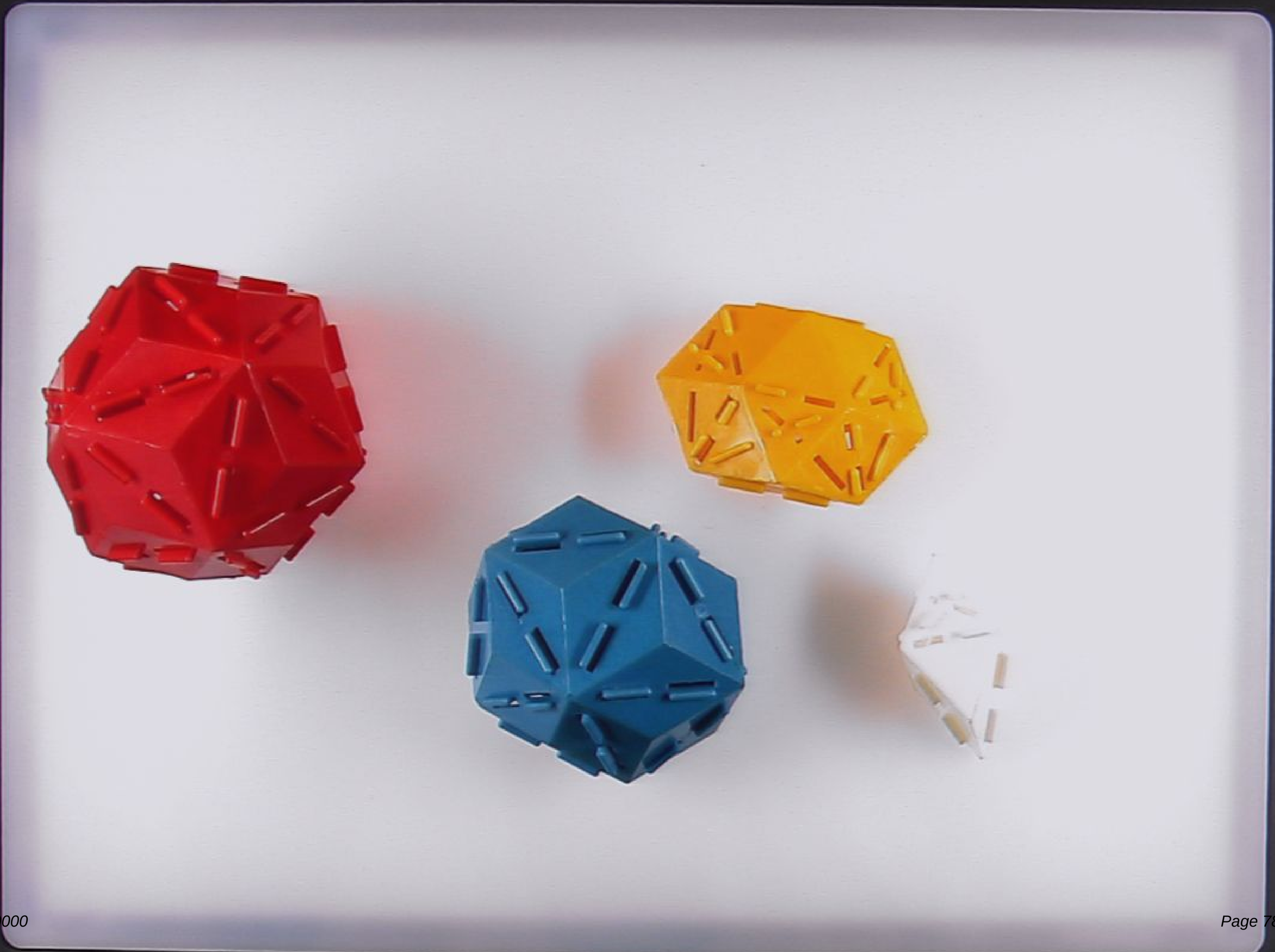


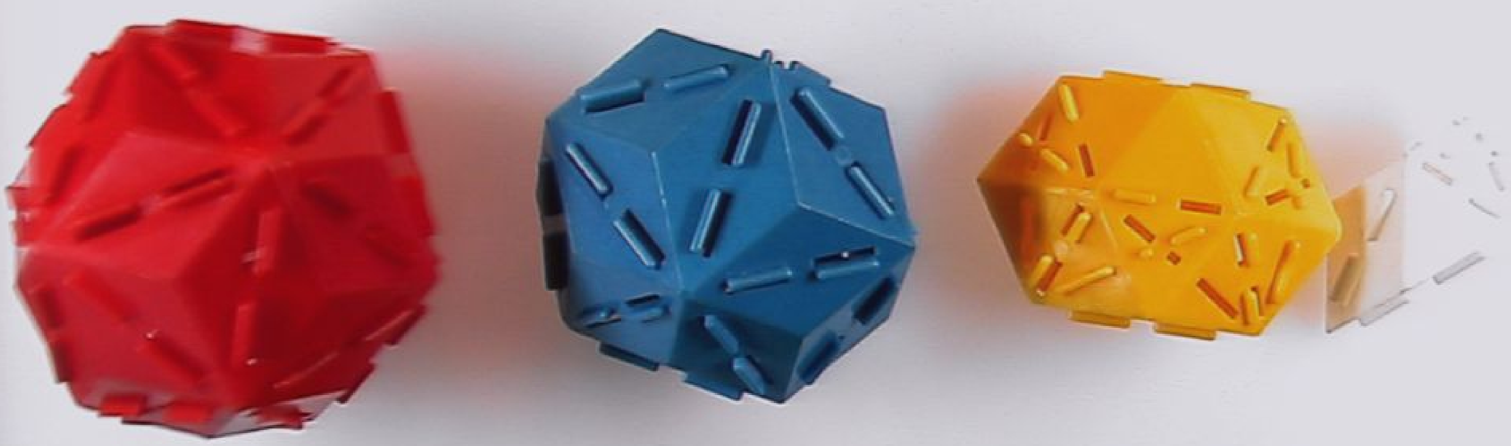


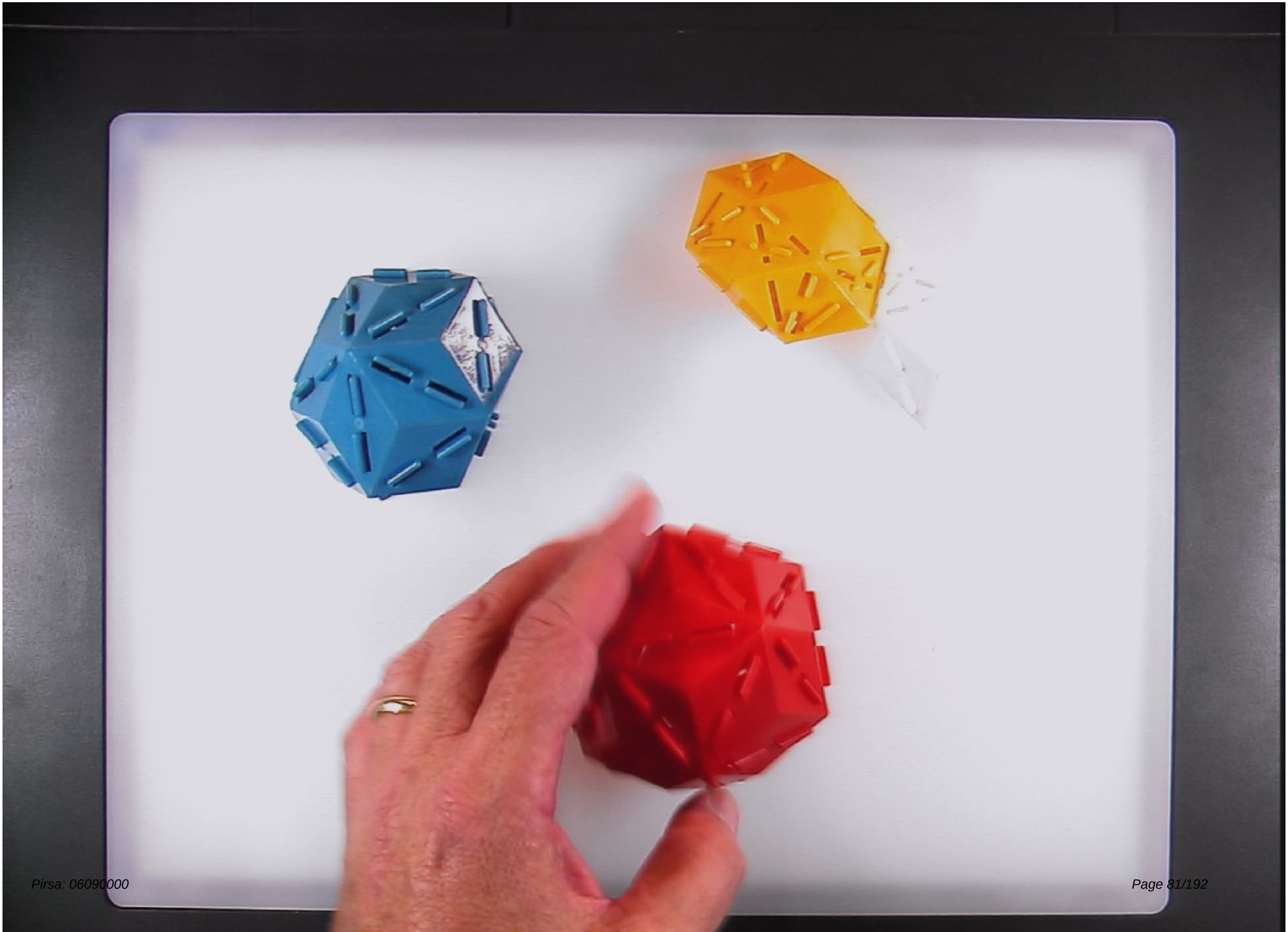


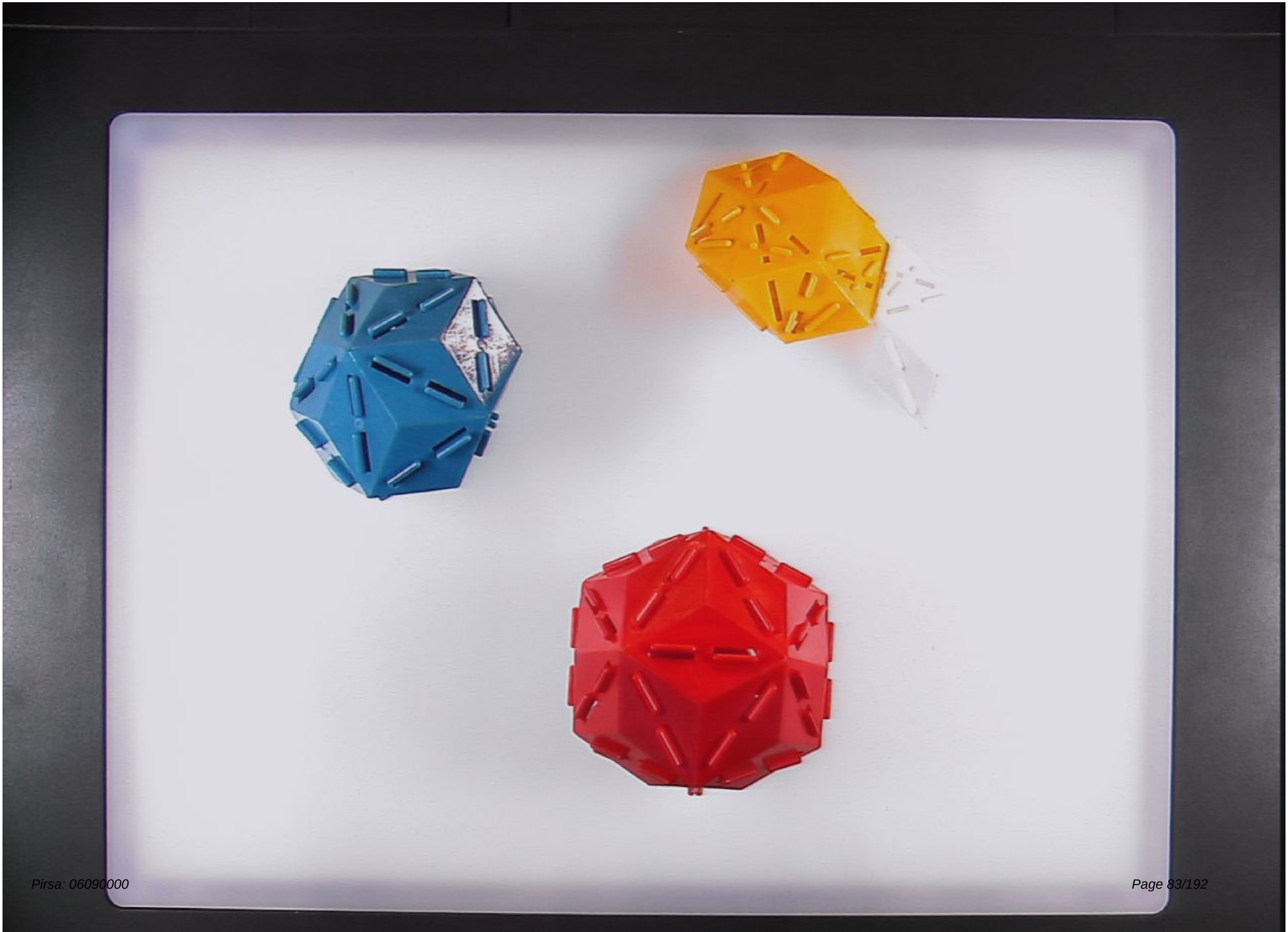


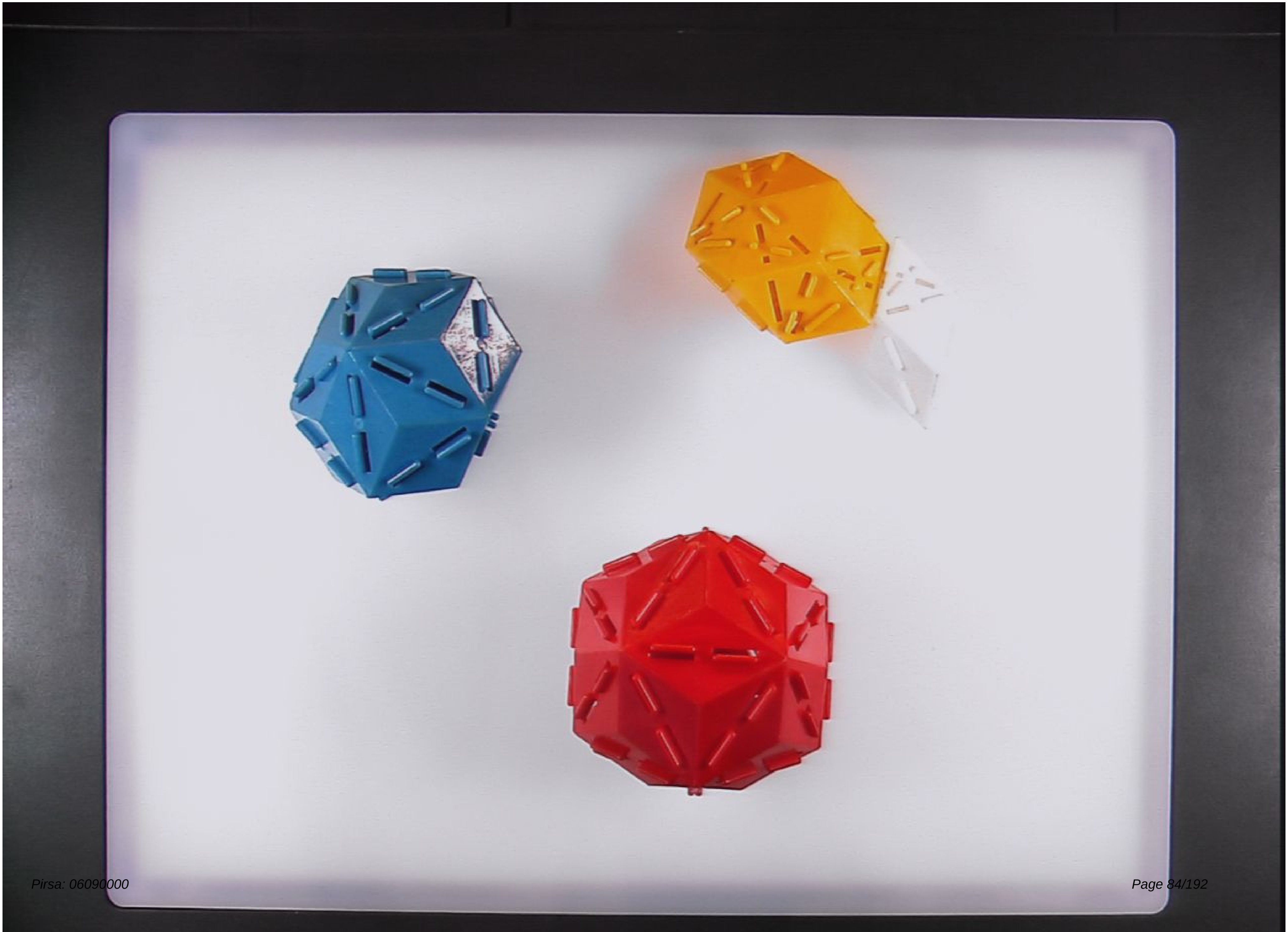


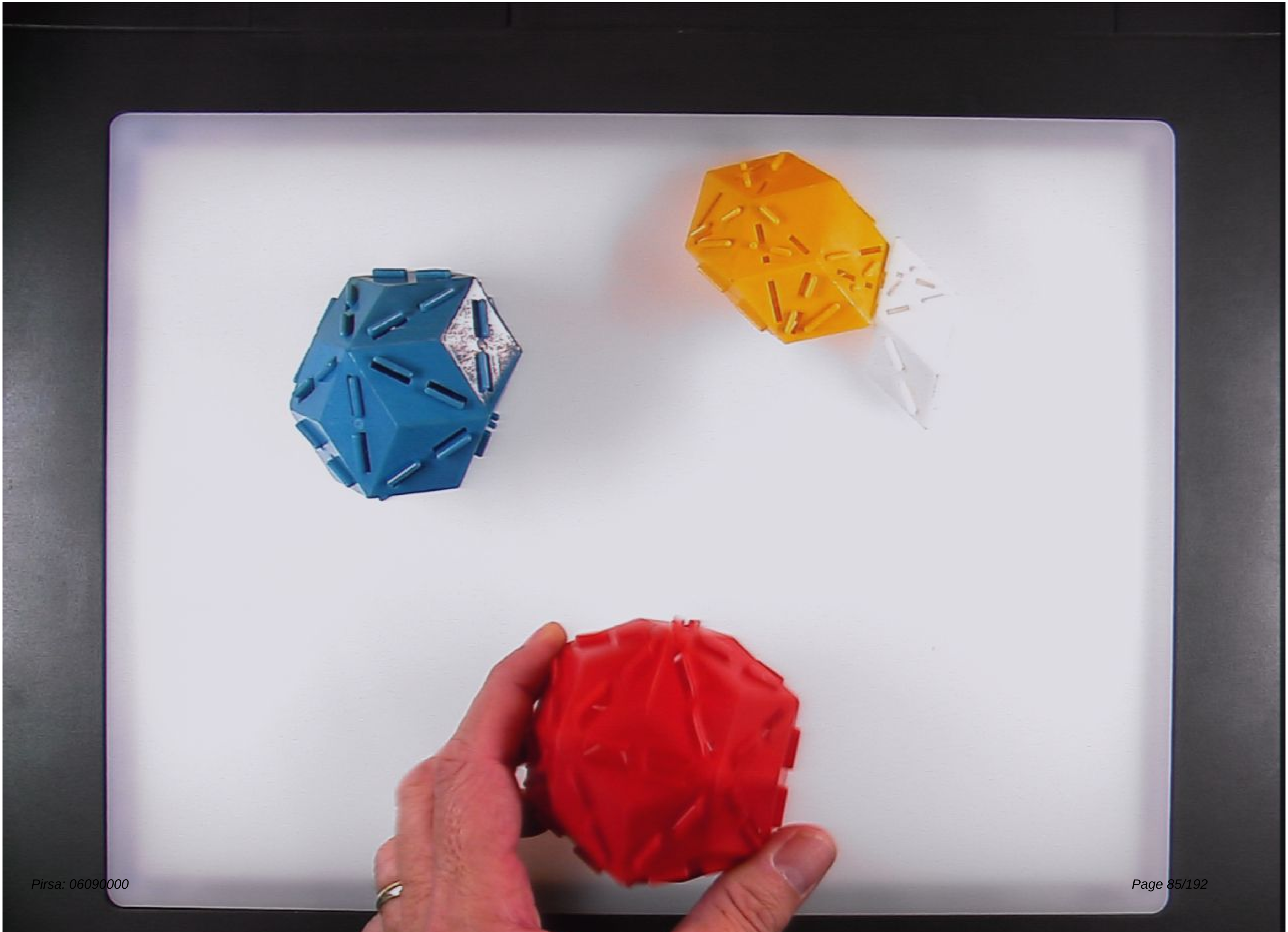


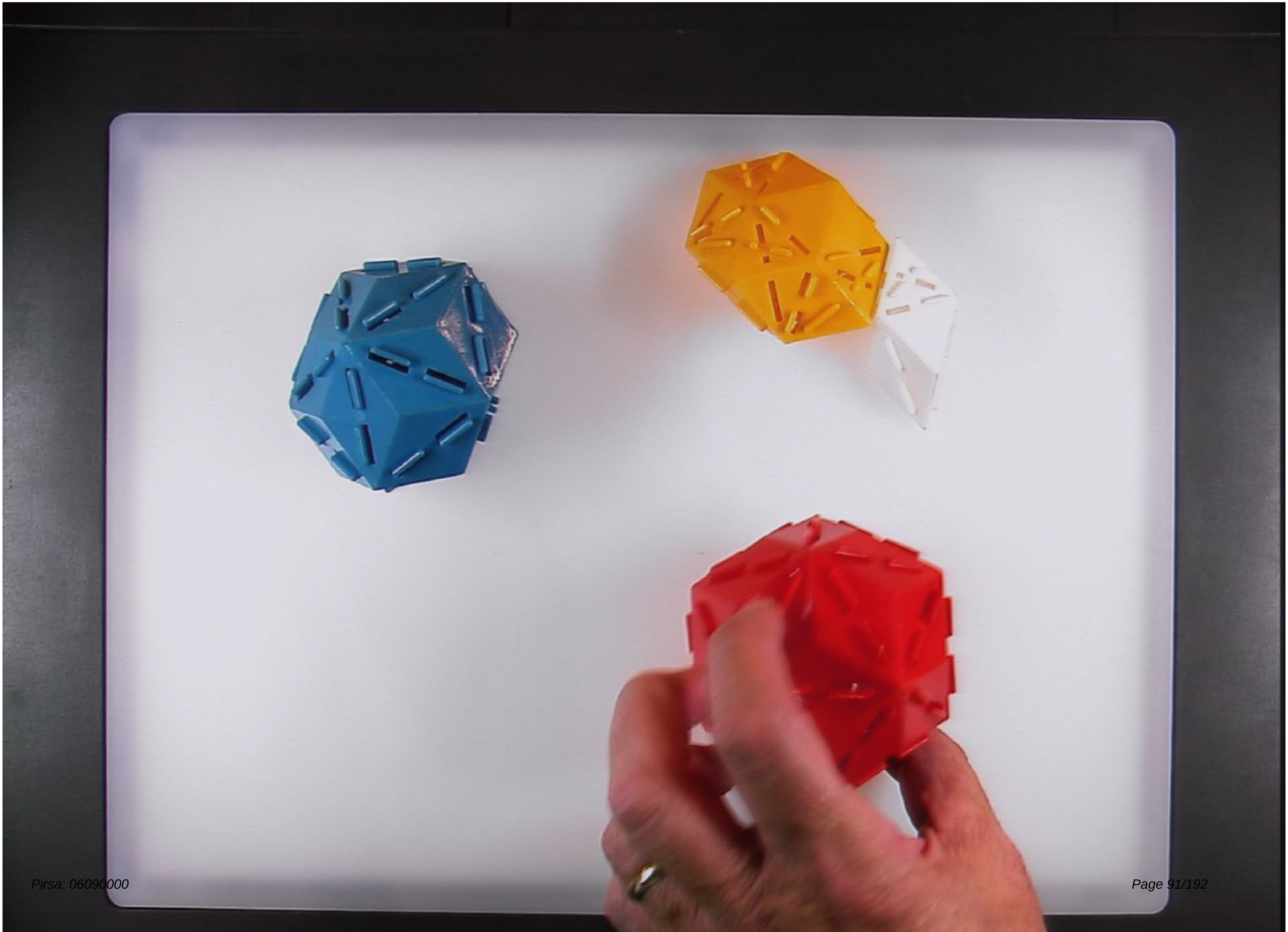


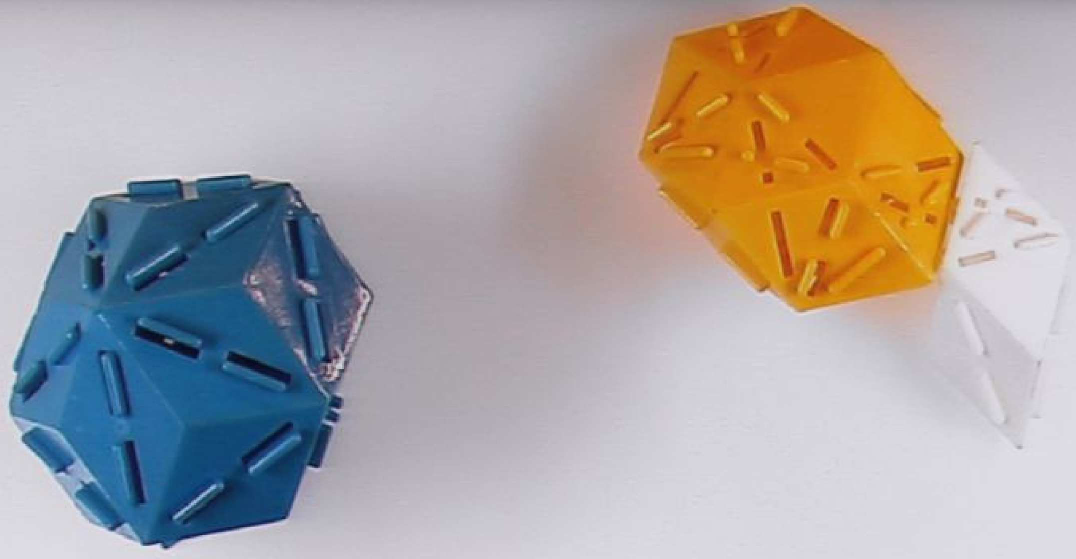


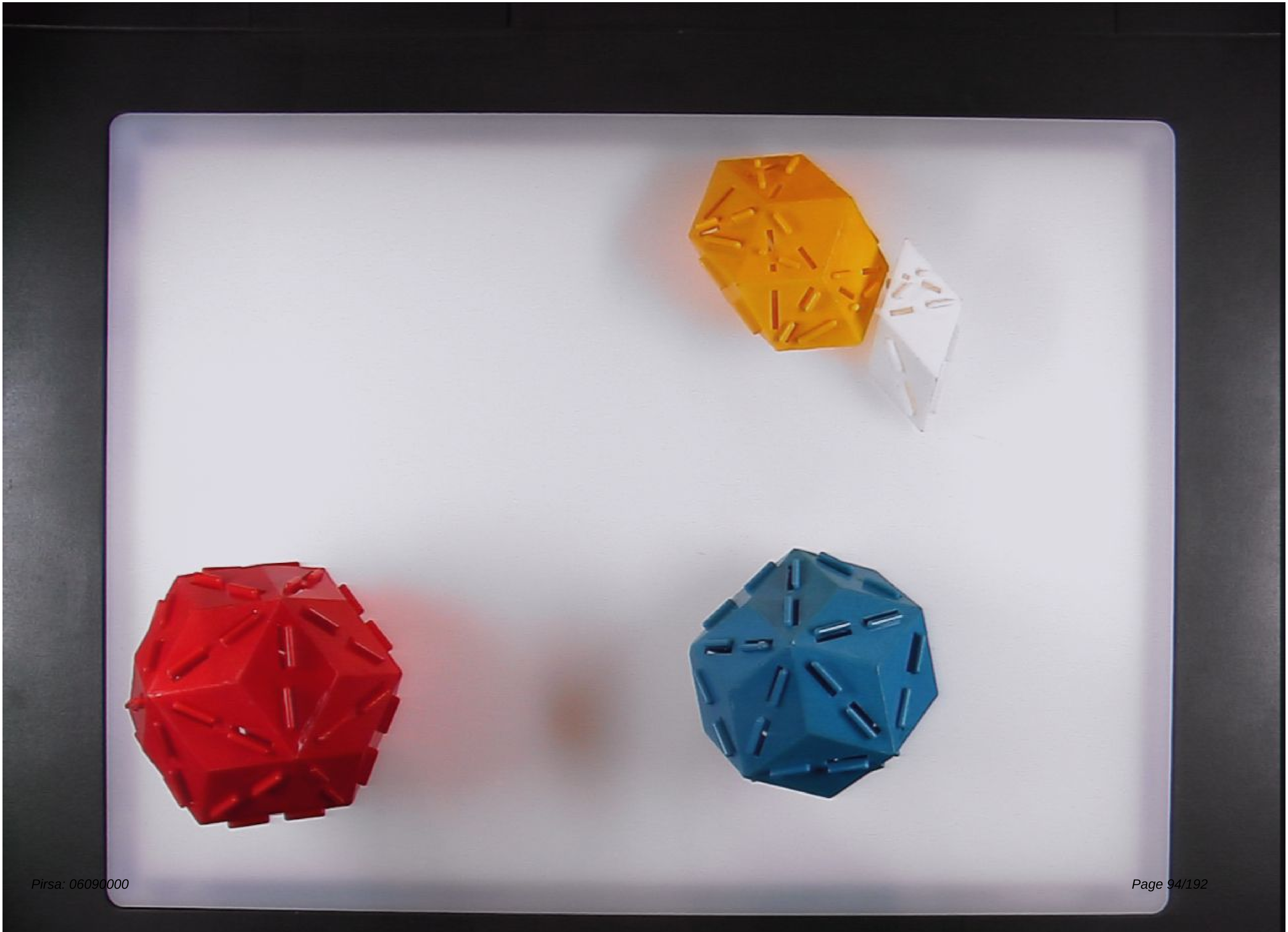


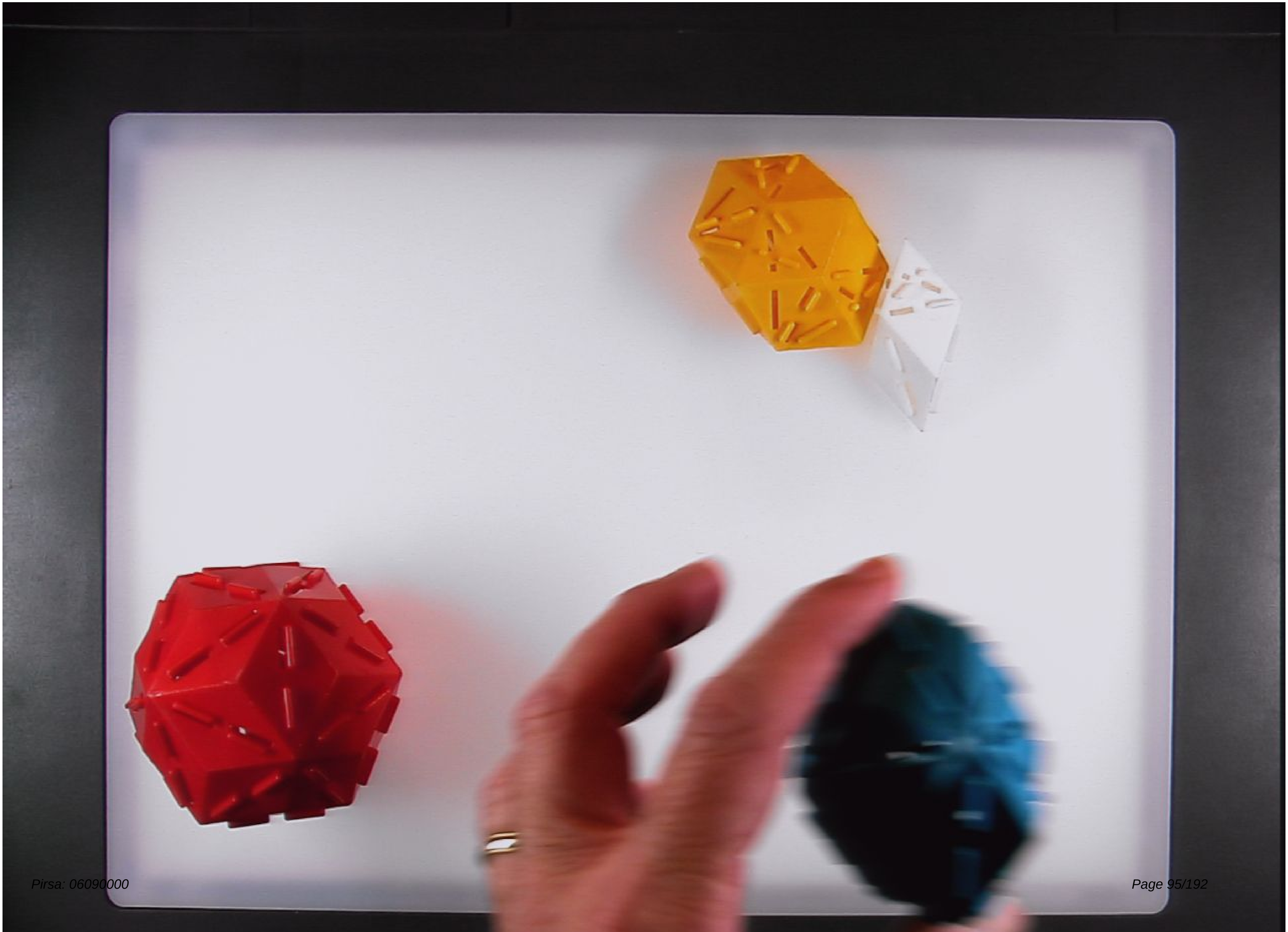


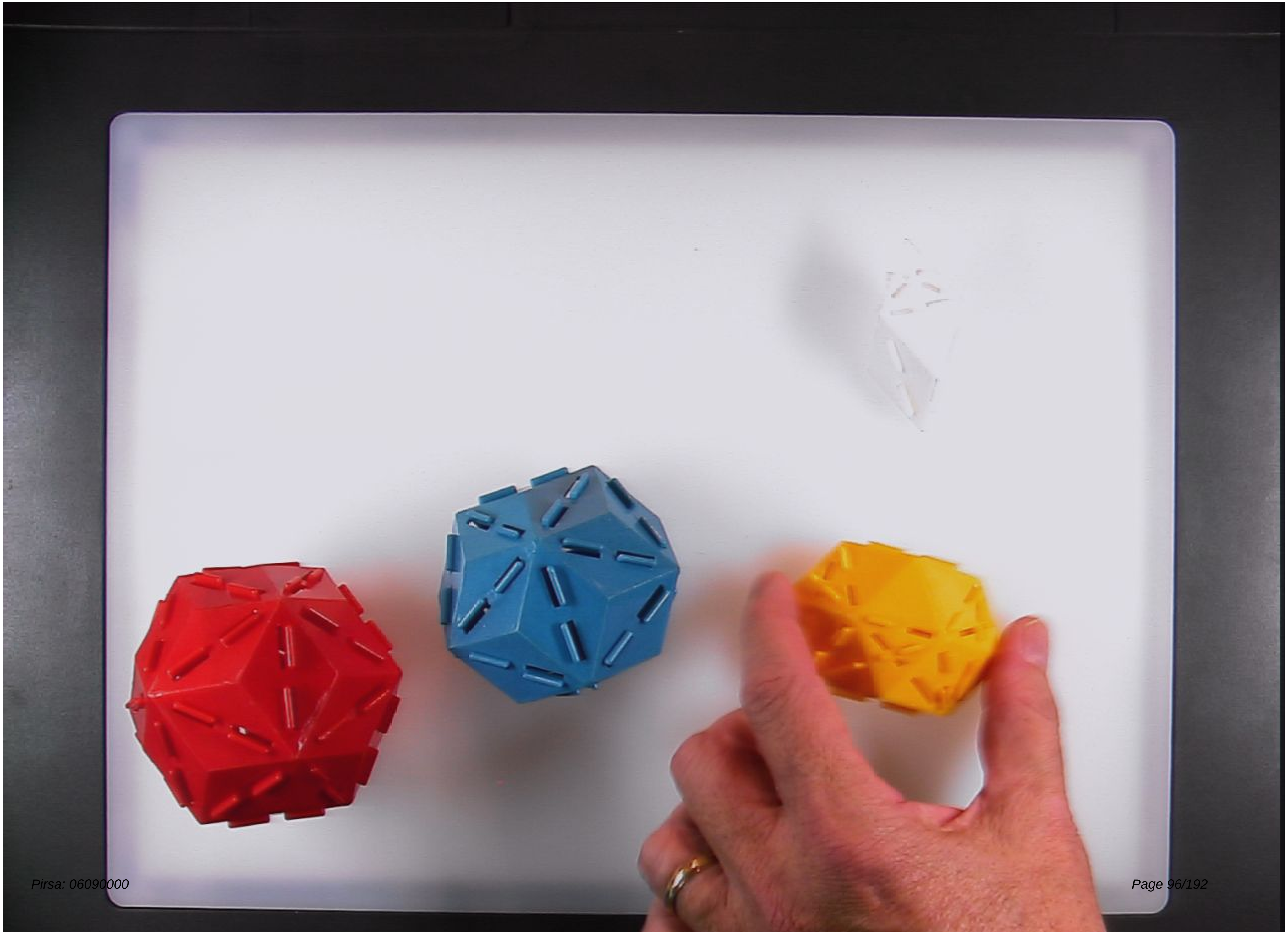


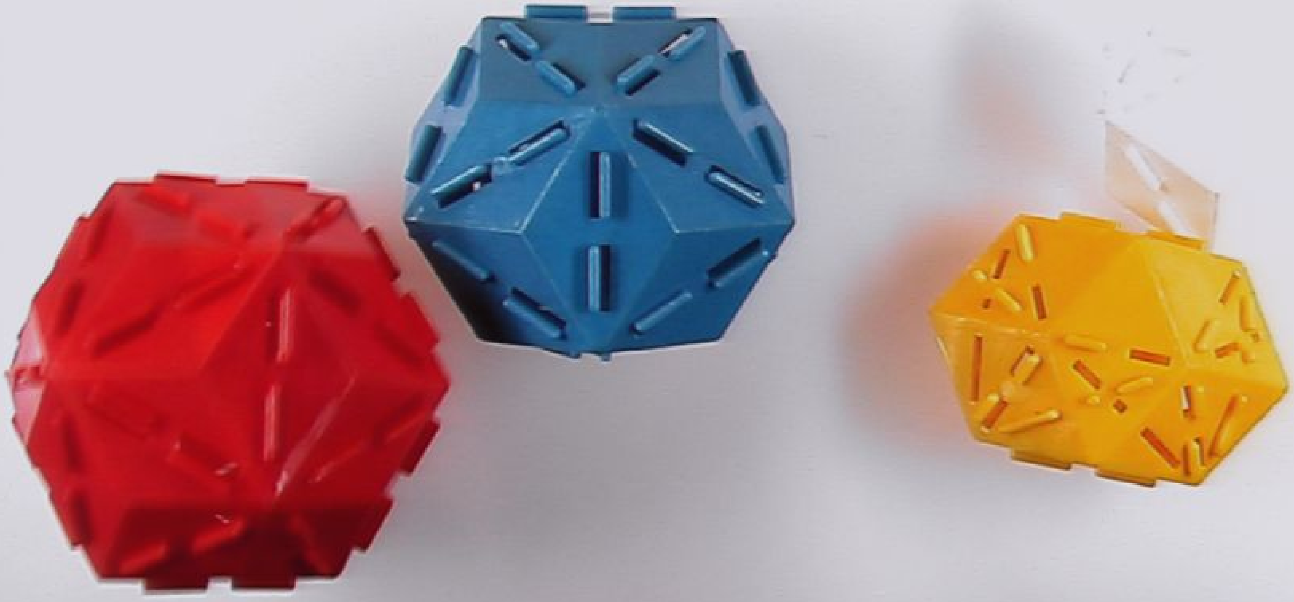


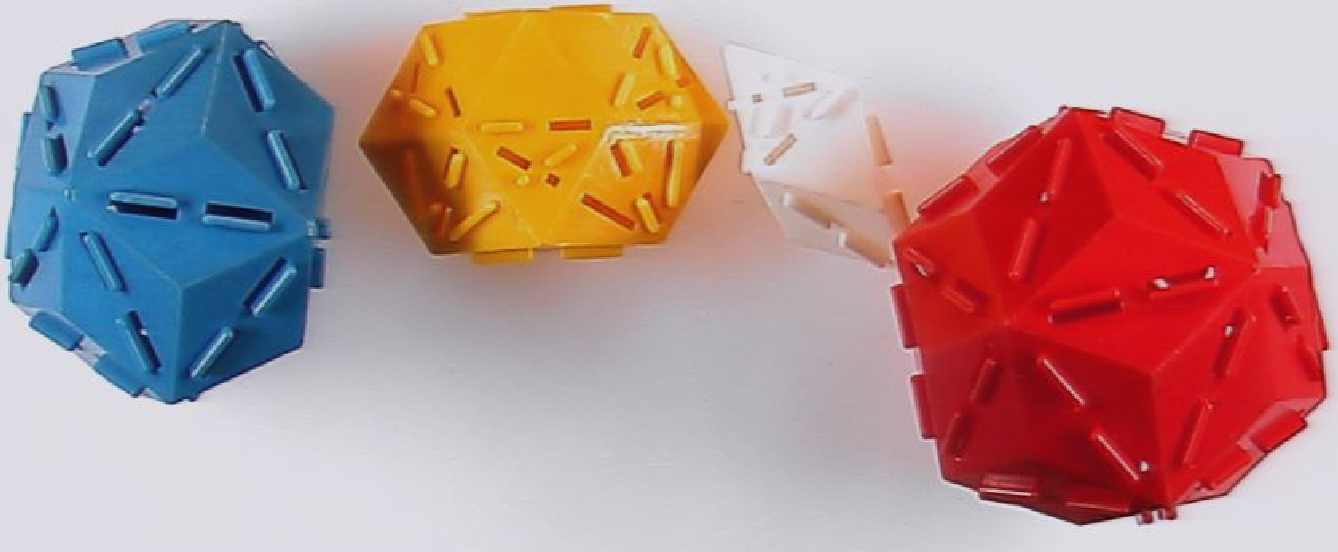


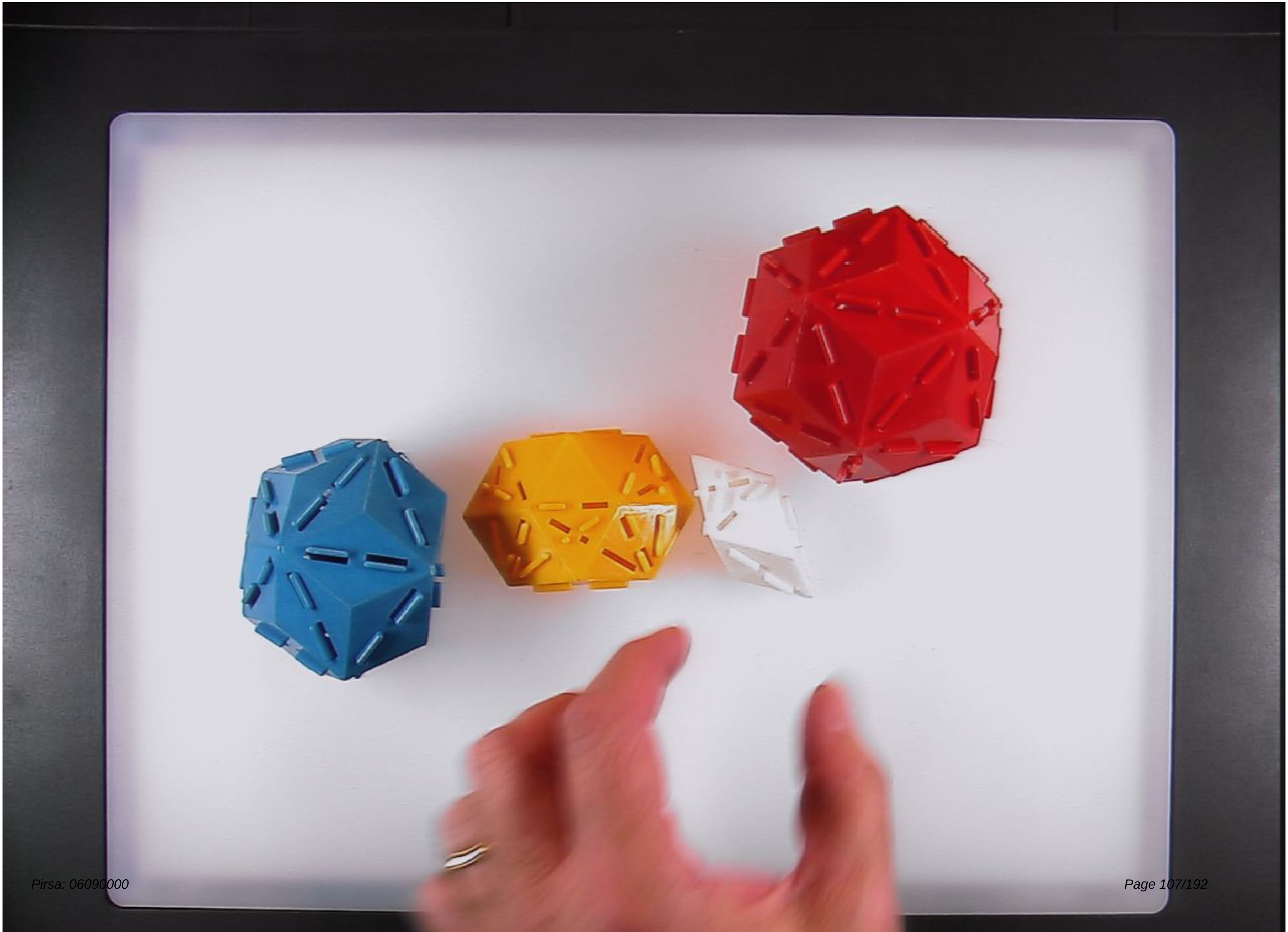


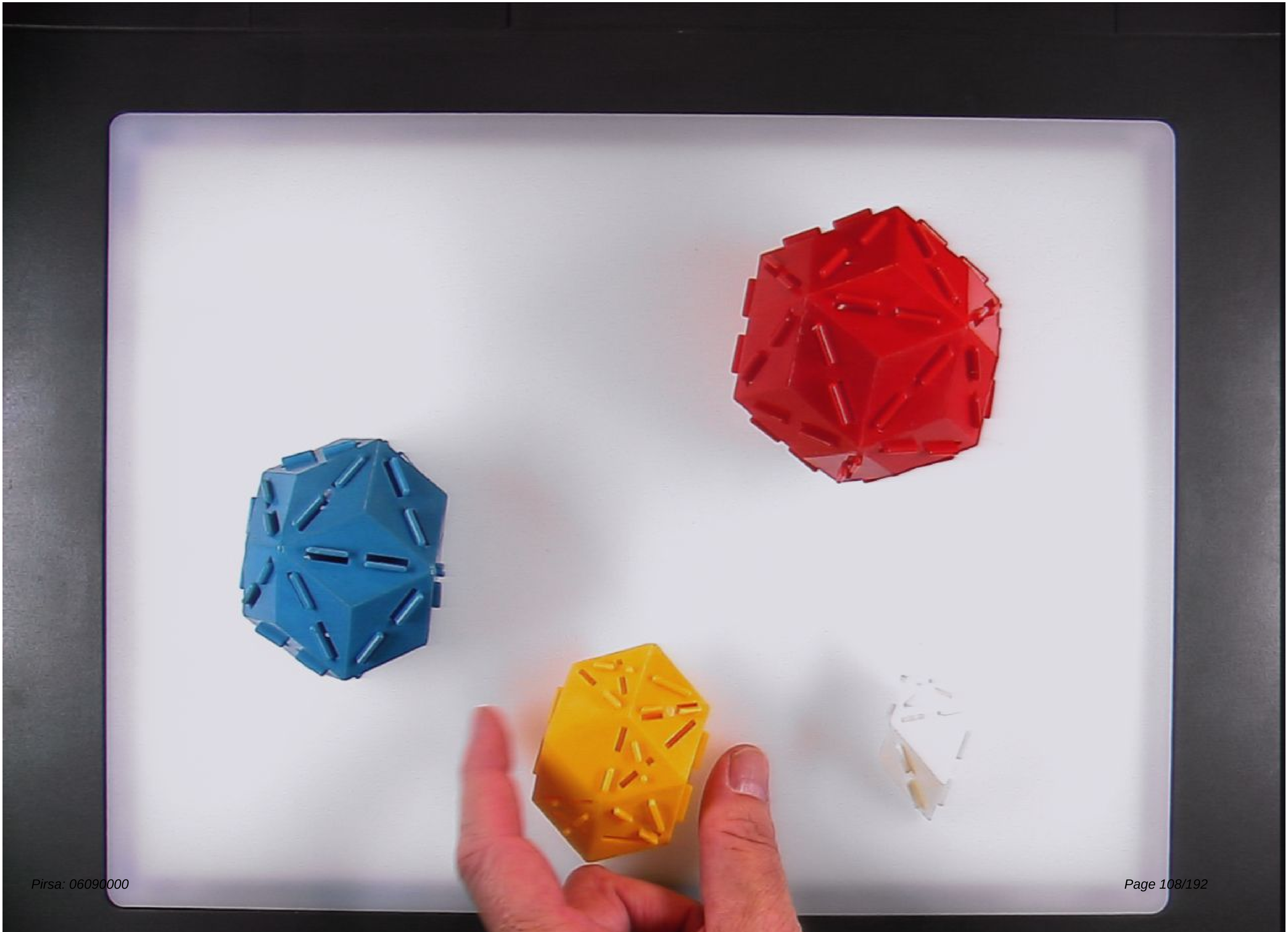


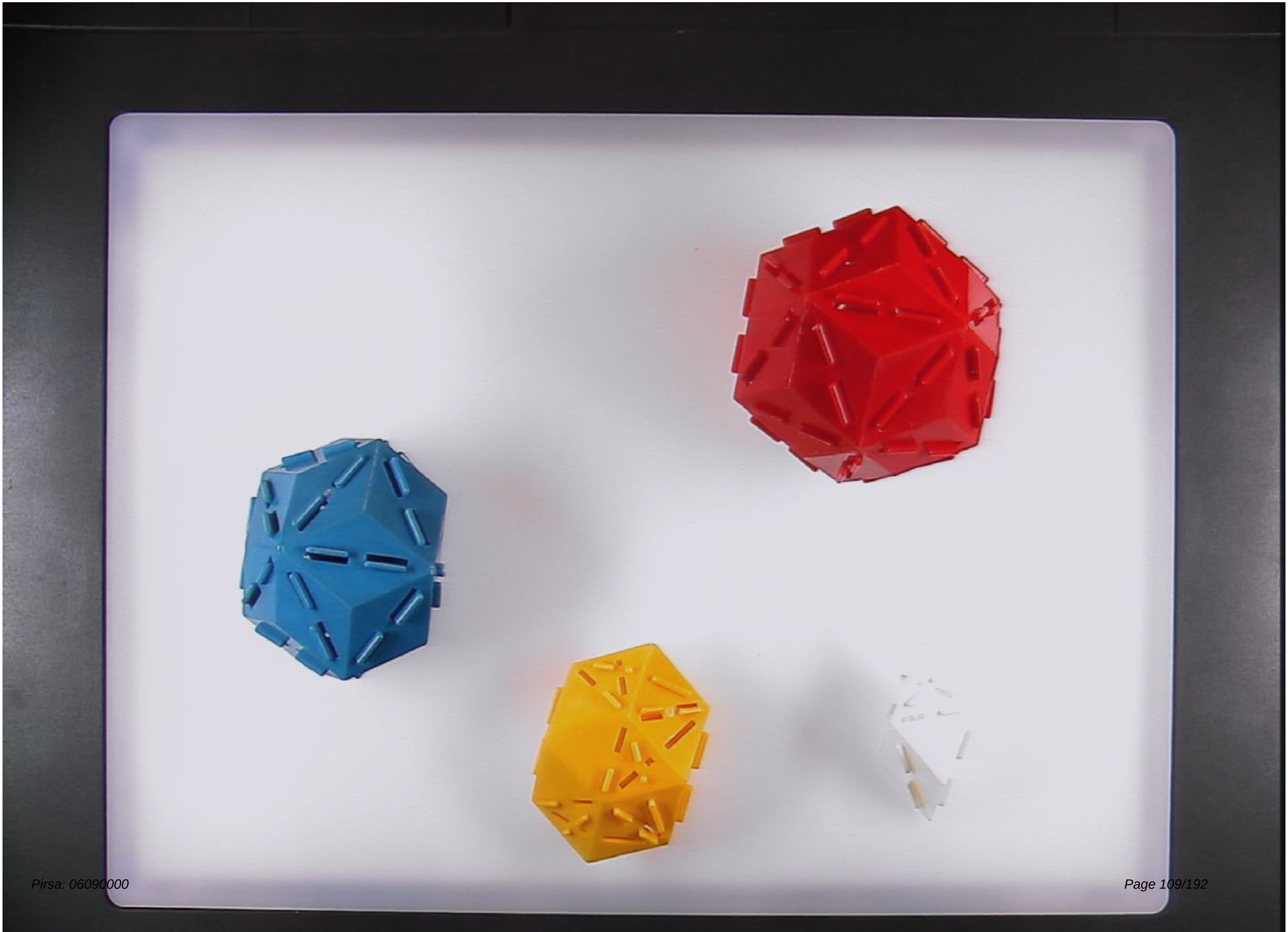


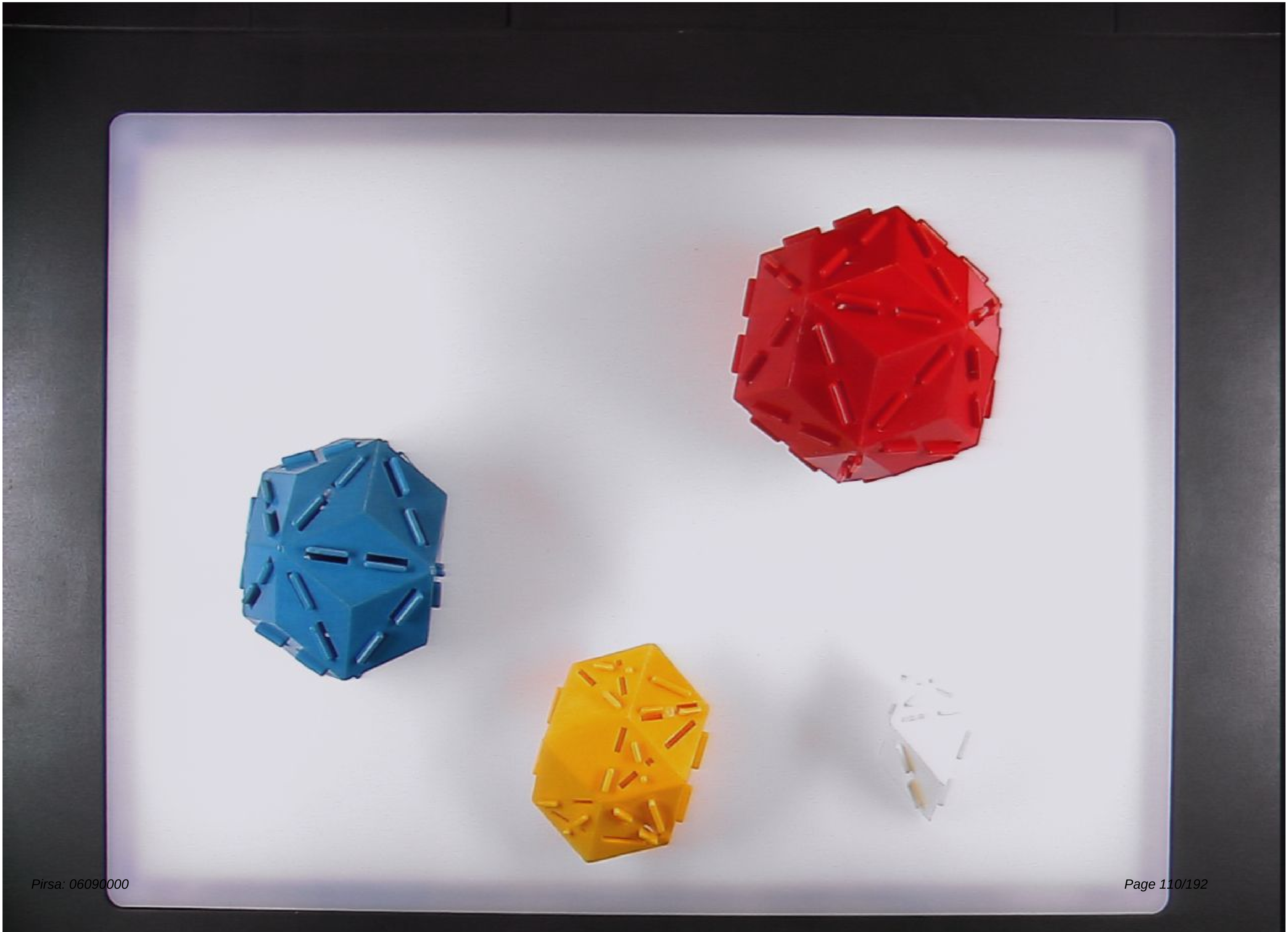


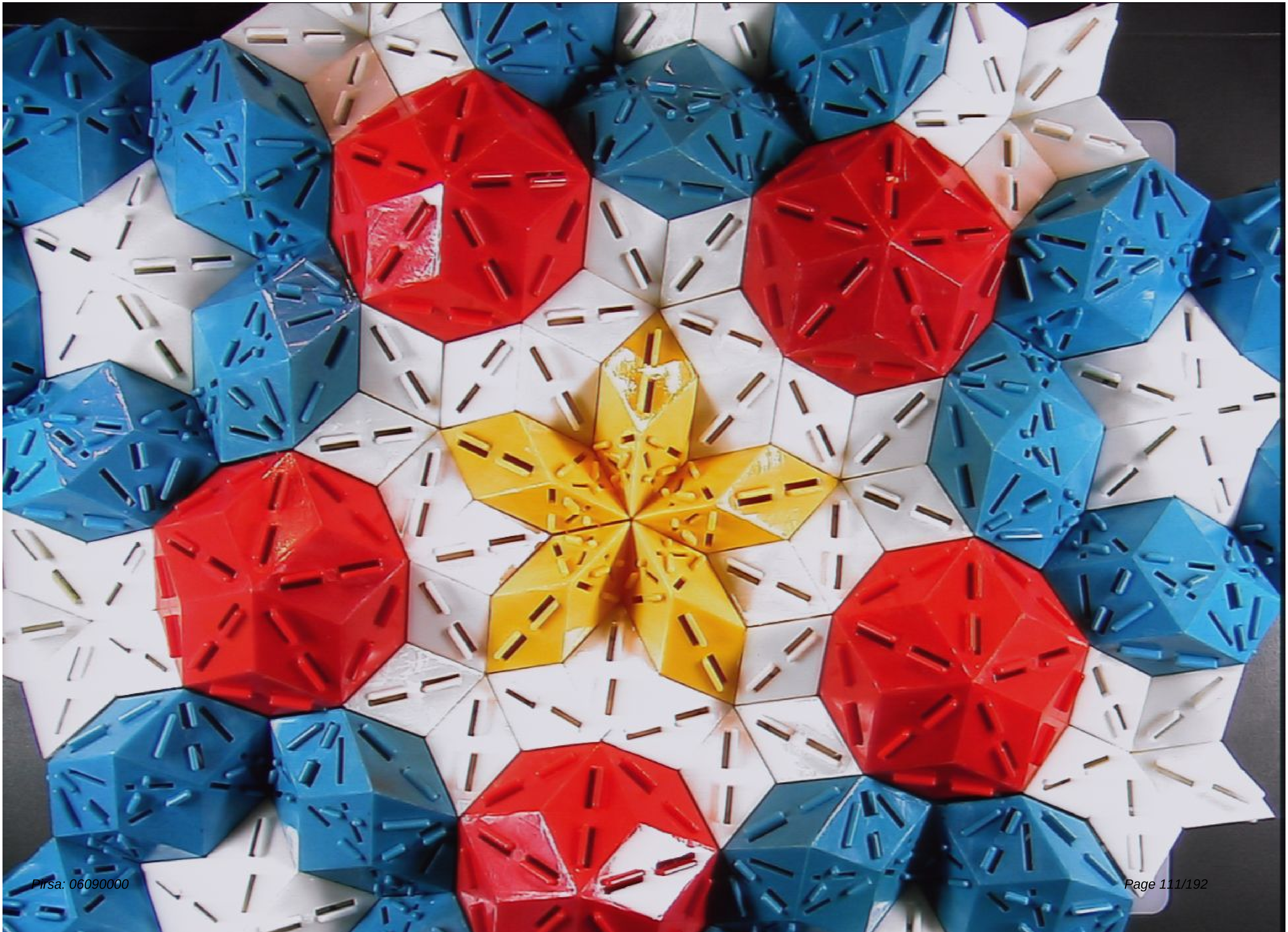


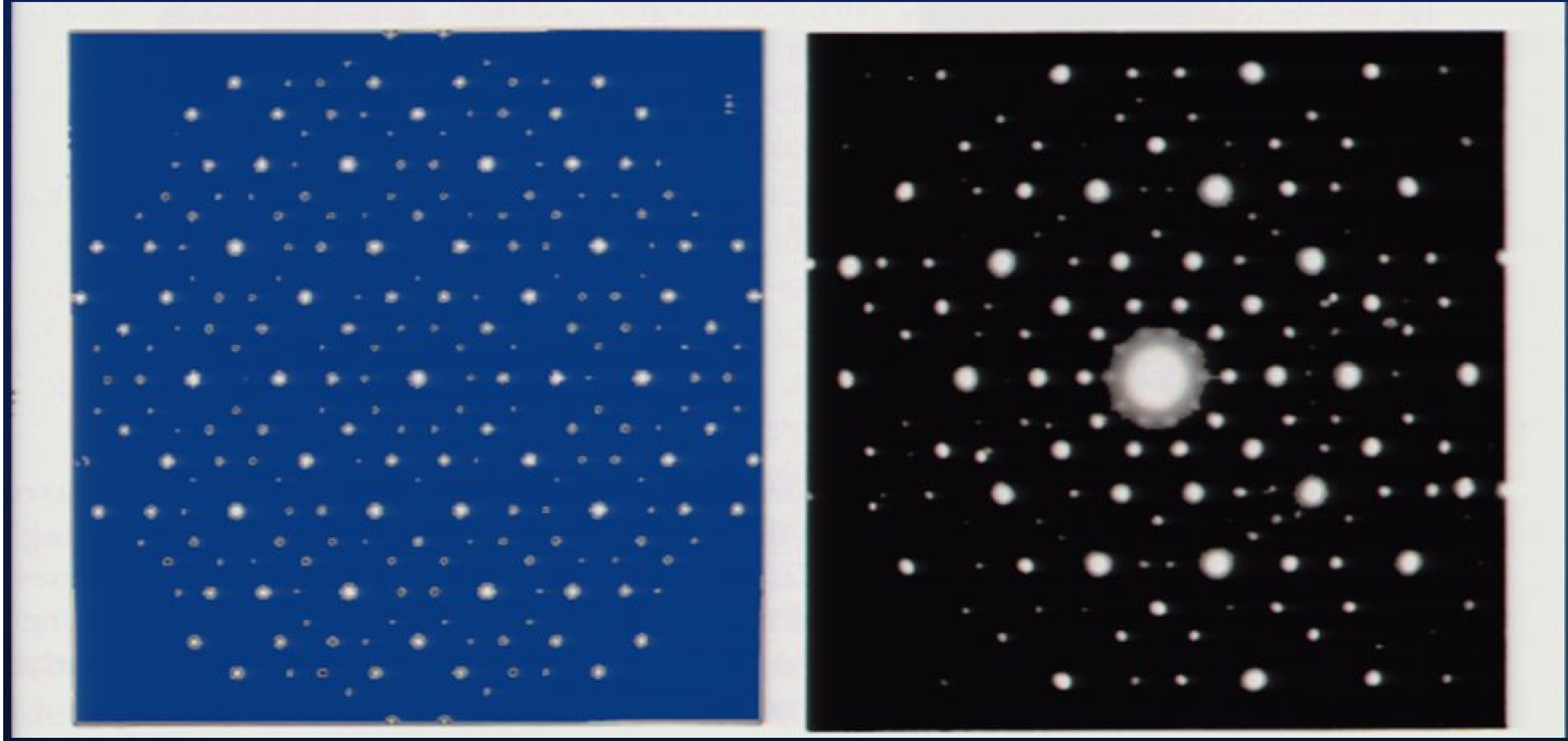




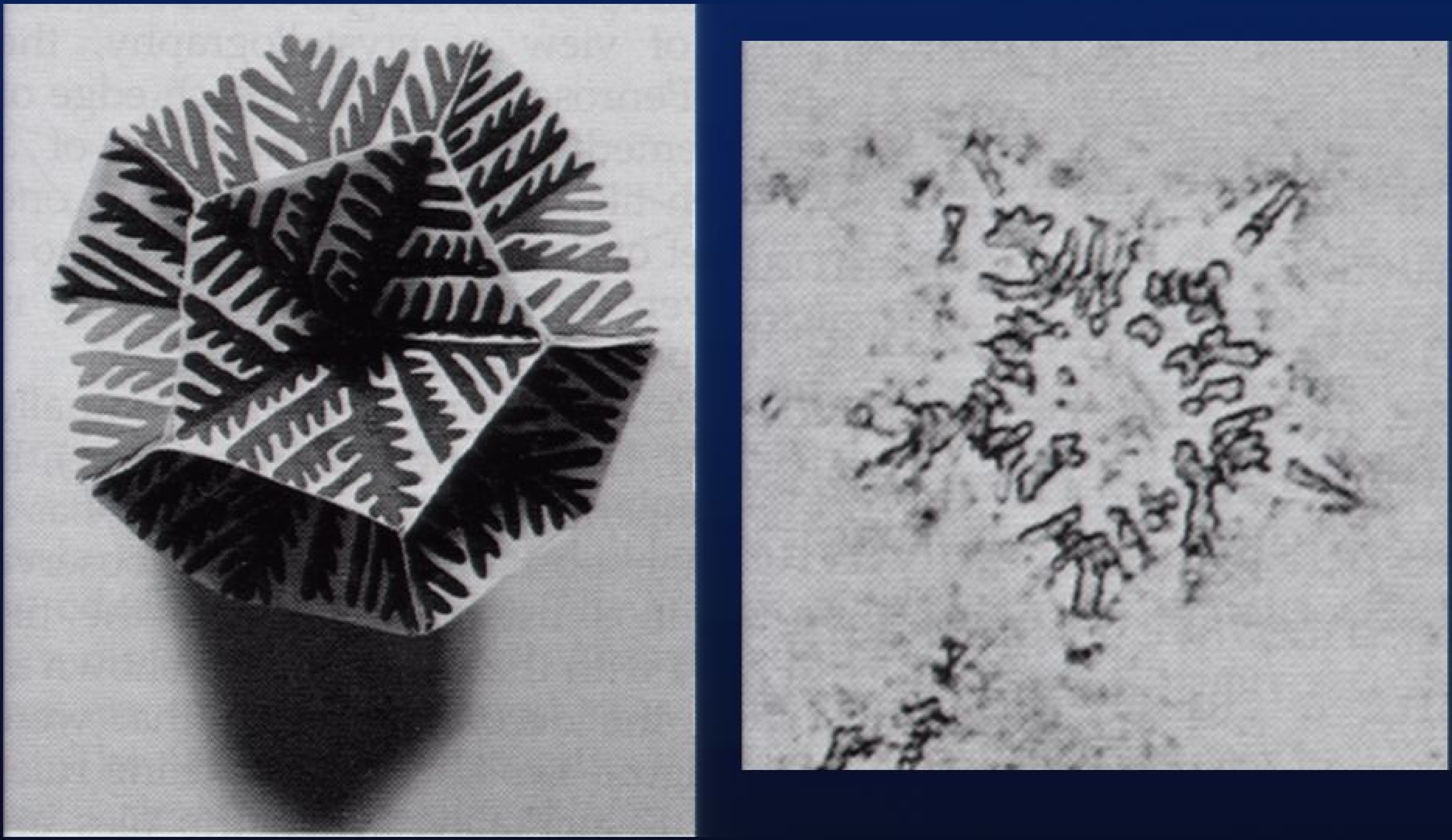


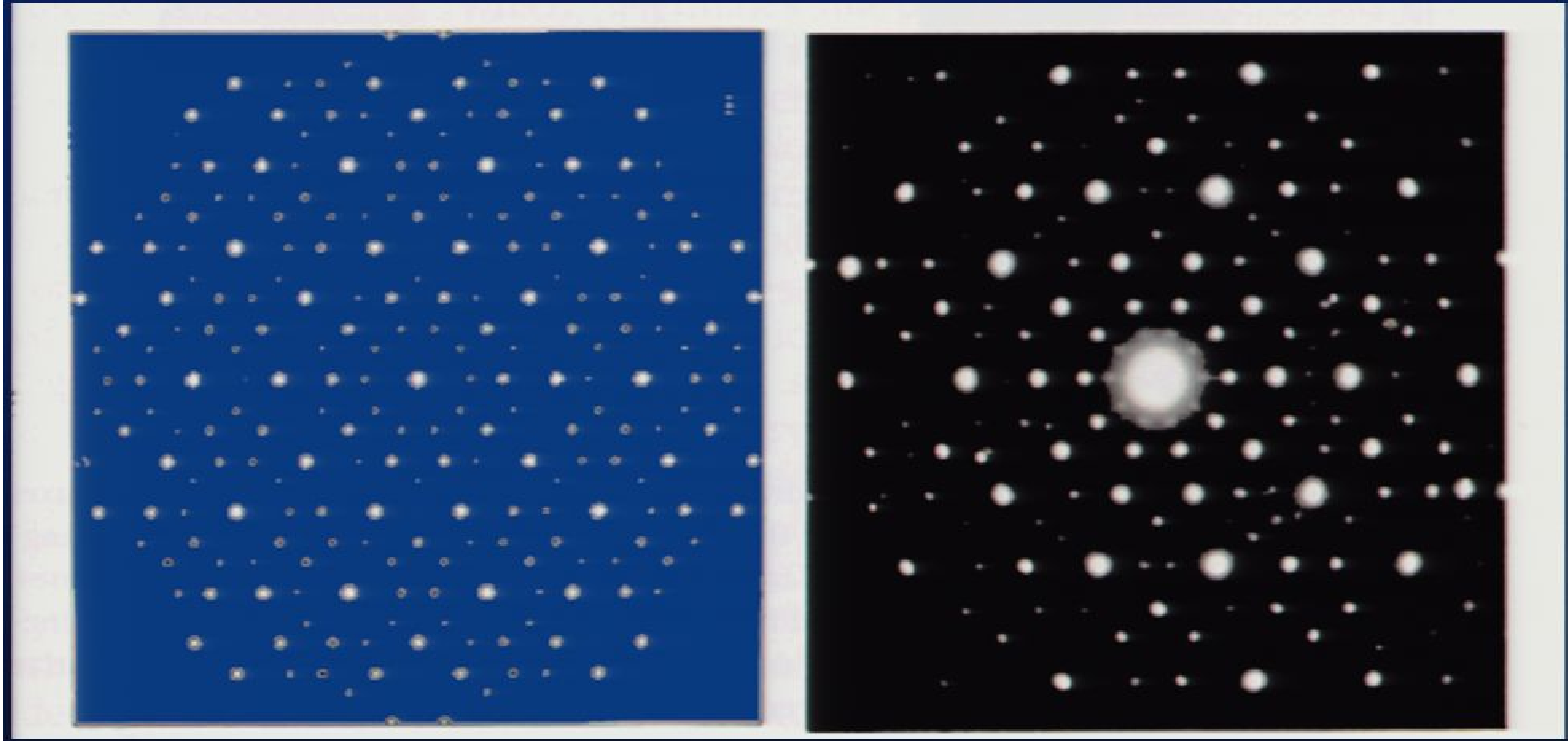






D. Levine and P.J. Steinhardt (1984)





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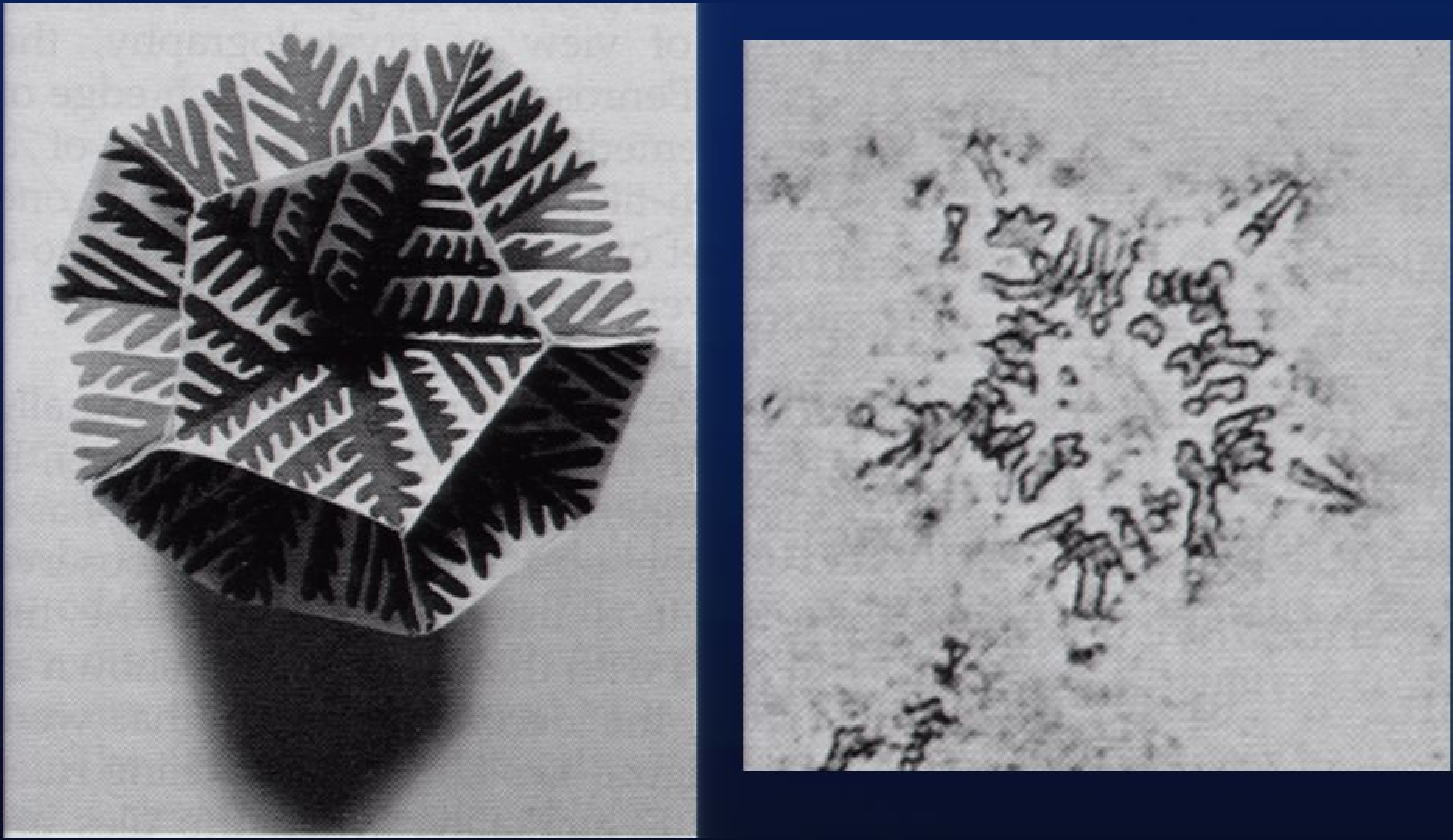

Reasons to be skeptical:

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in order to grow?

Two or more repeating units
with complex rules for how to join:
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Non-local Growth Rules ?

...LSLLSLSLLSLLSLSLLSLSL ...

Non-local Growth Rules ?

...LSLLSLSLLSLLSLSLLSLSL ...

Non-local Growth Rules ?

...LSLLSLSLLSLLSLSLLSLSL ...

LSLSLLSLSLLSL

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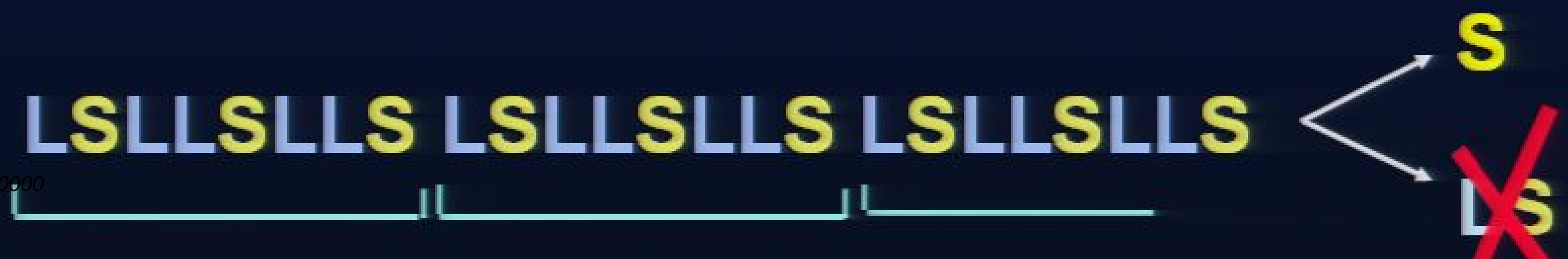
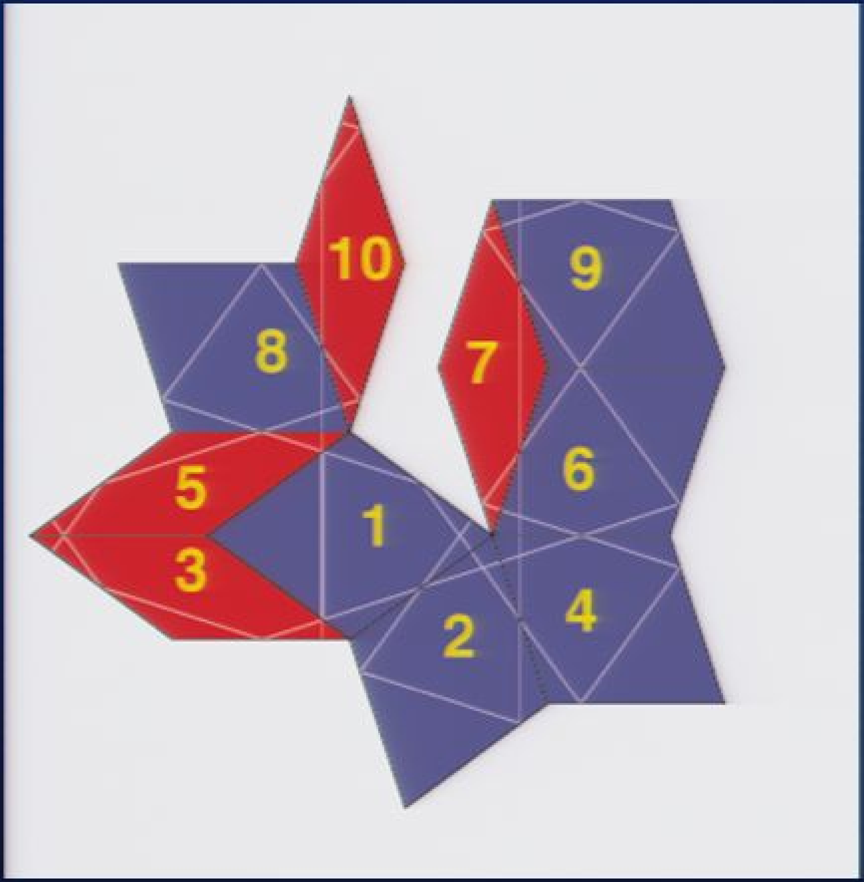
Non-local Growth Rules ?

...LSLLSLSLLSLLSLSLLSLSL ...


LSLSLLSLSLLSL

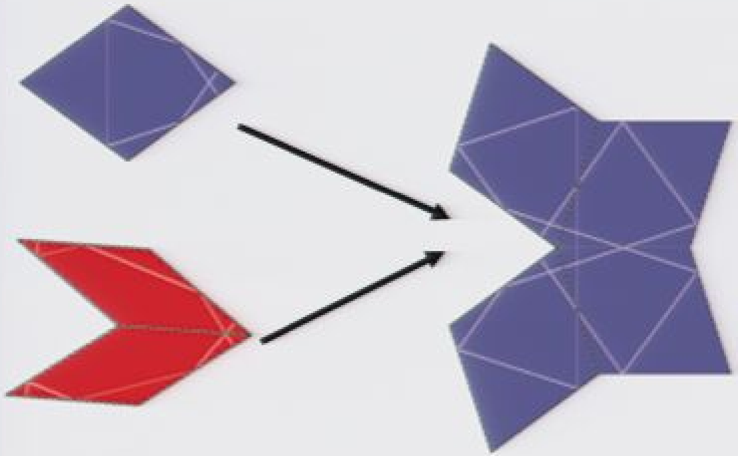

LSLLSLLS LSLLSLLS LSLLSLLS



Penrose Rules <u>Don't</u> Guarantee a Perfect Tiling

Question:

Can we make a modest improvement using differerent rules for when to add tiles!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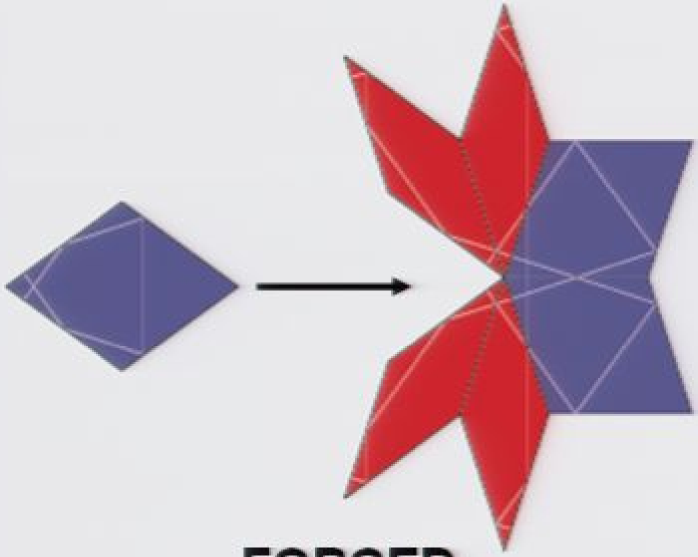
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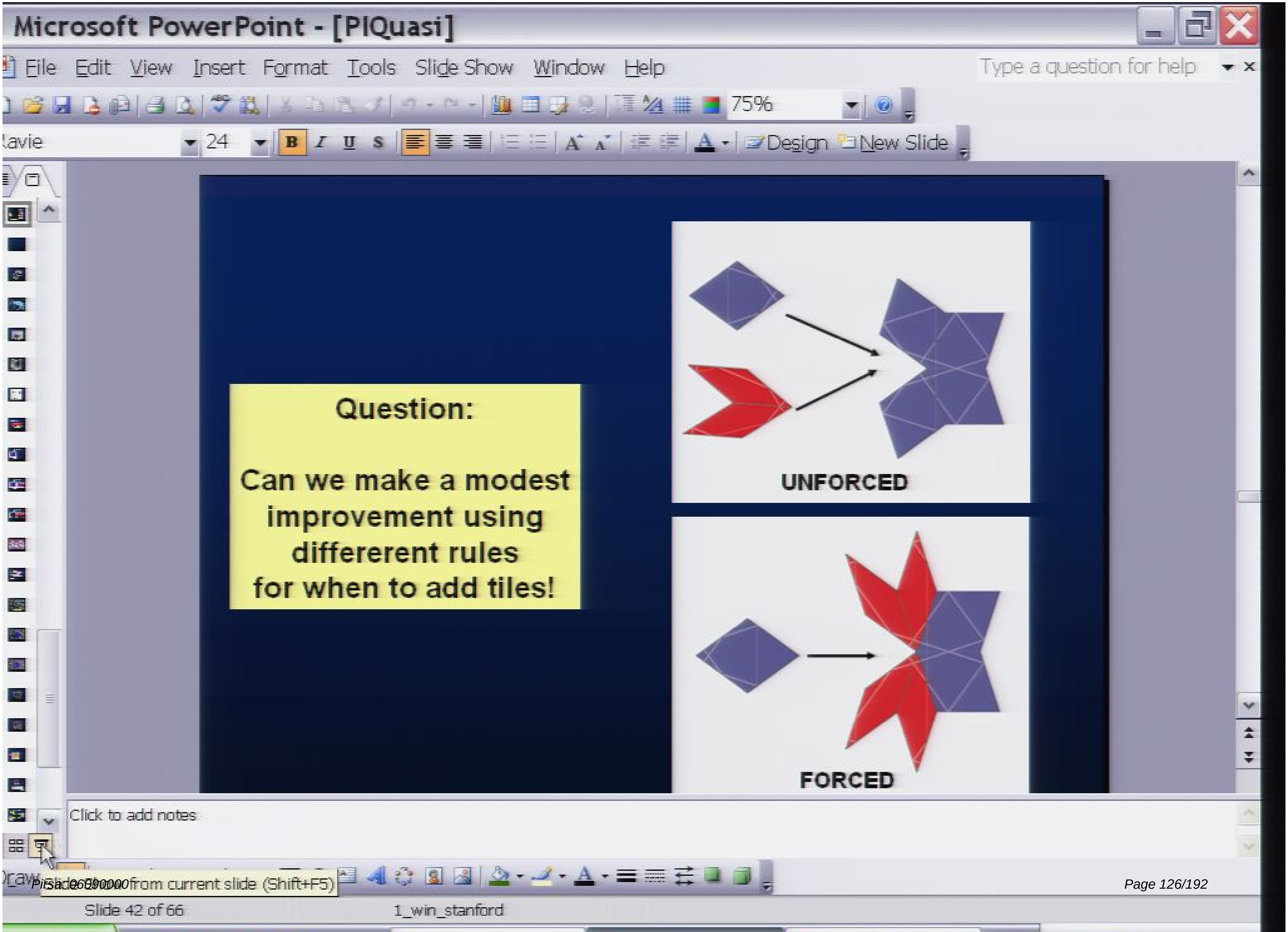

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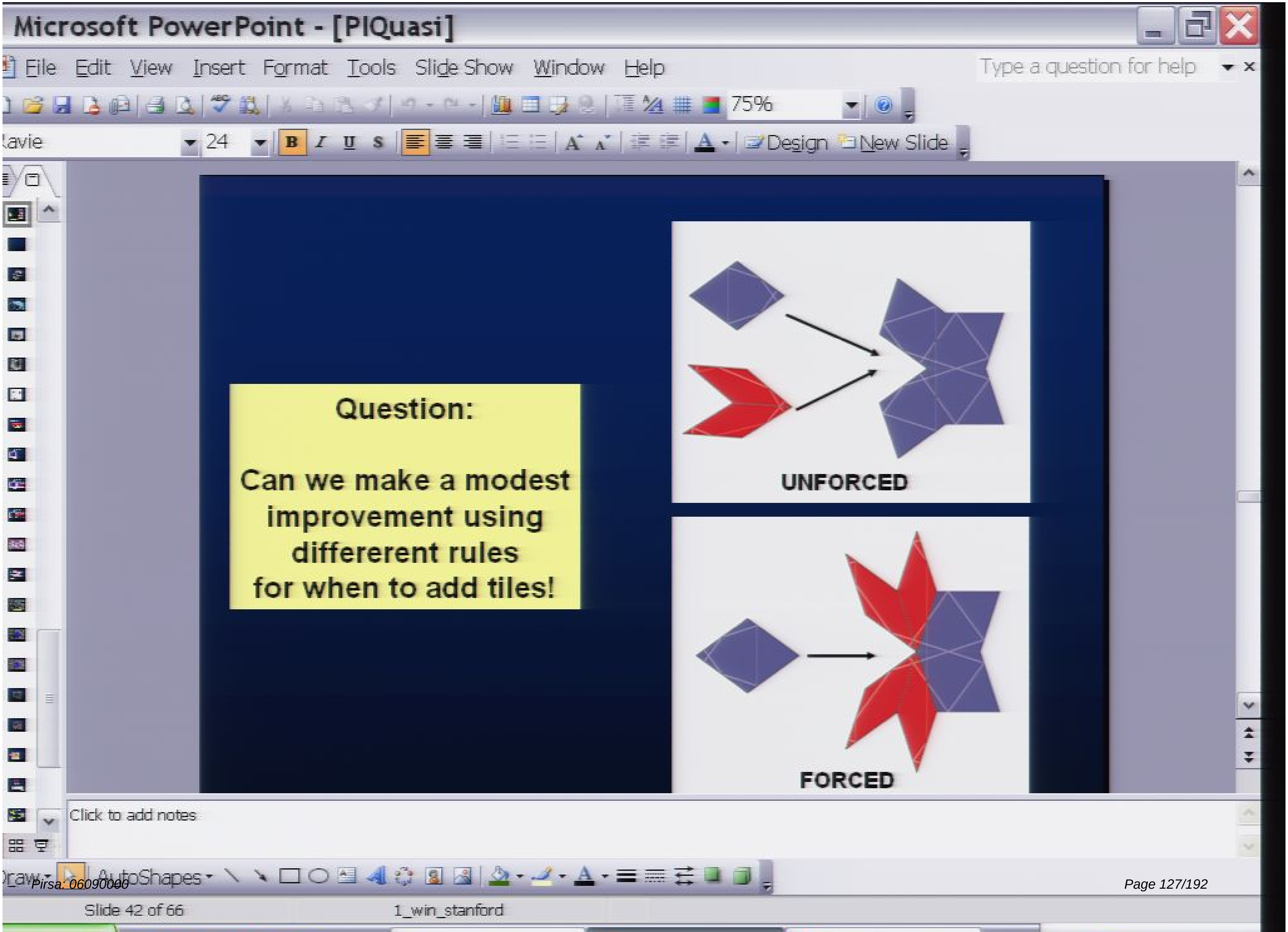

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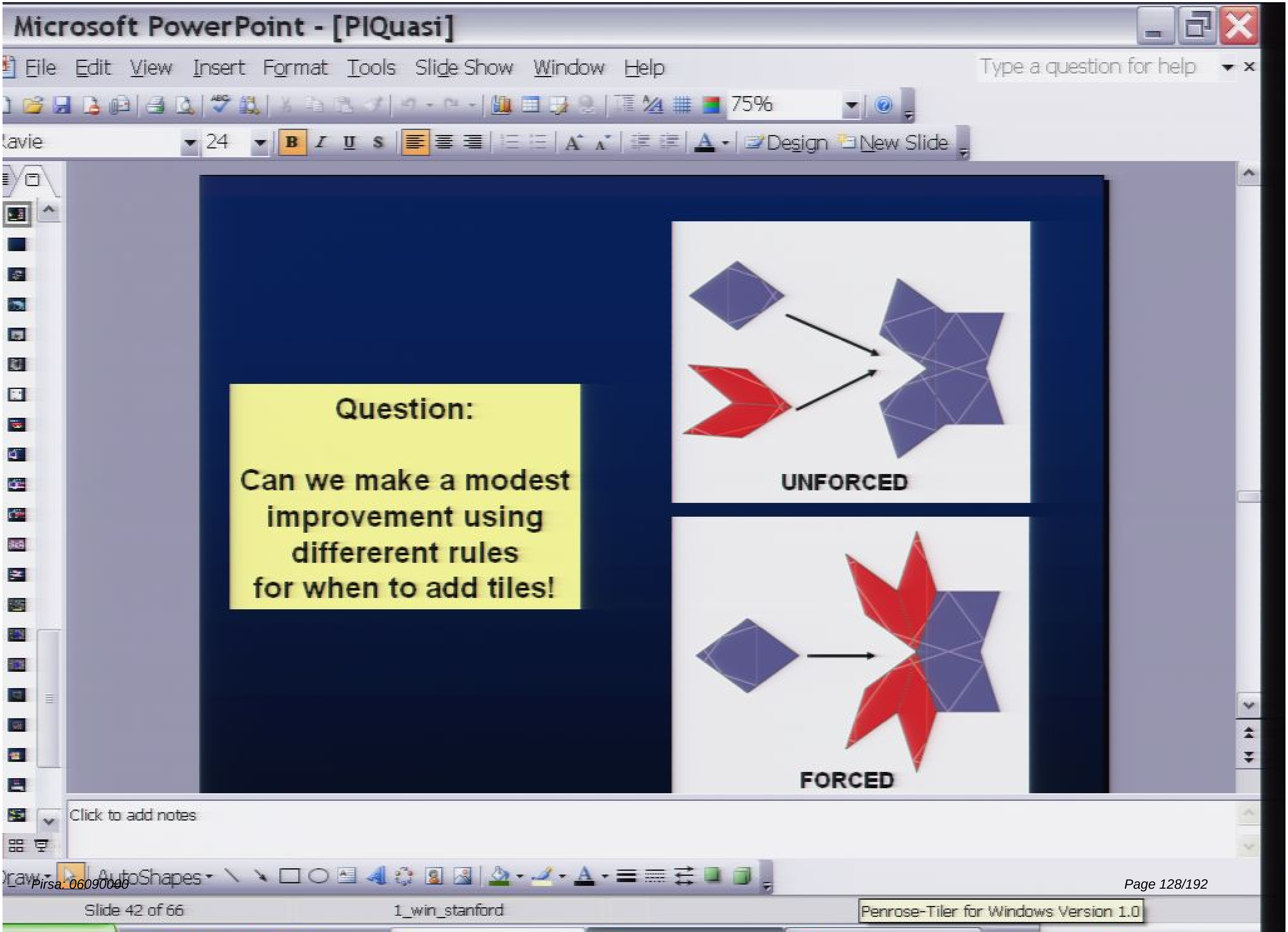

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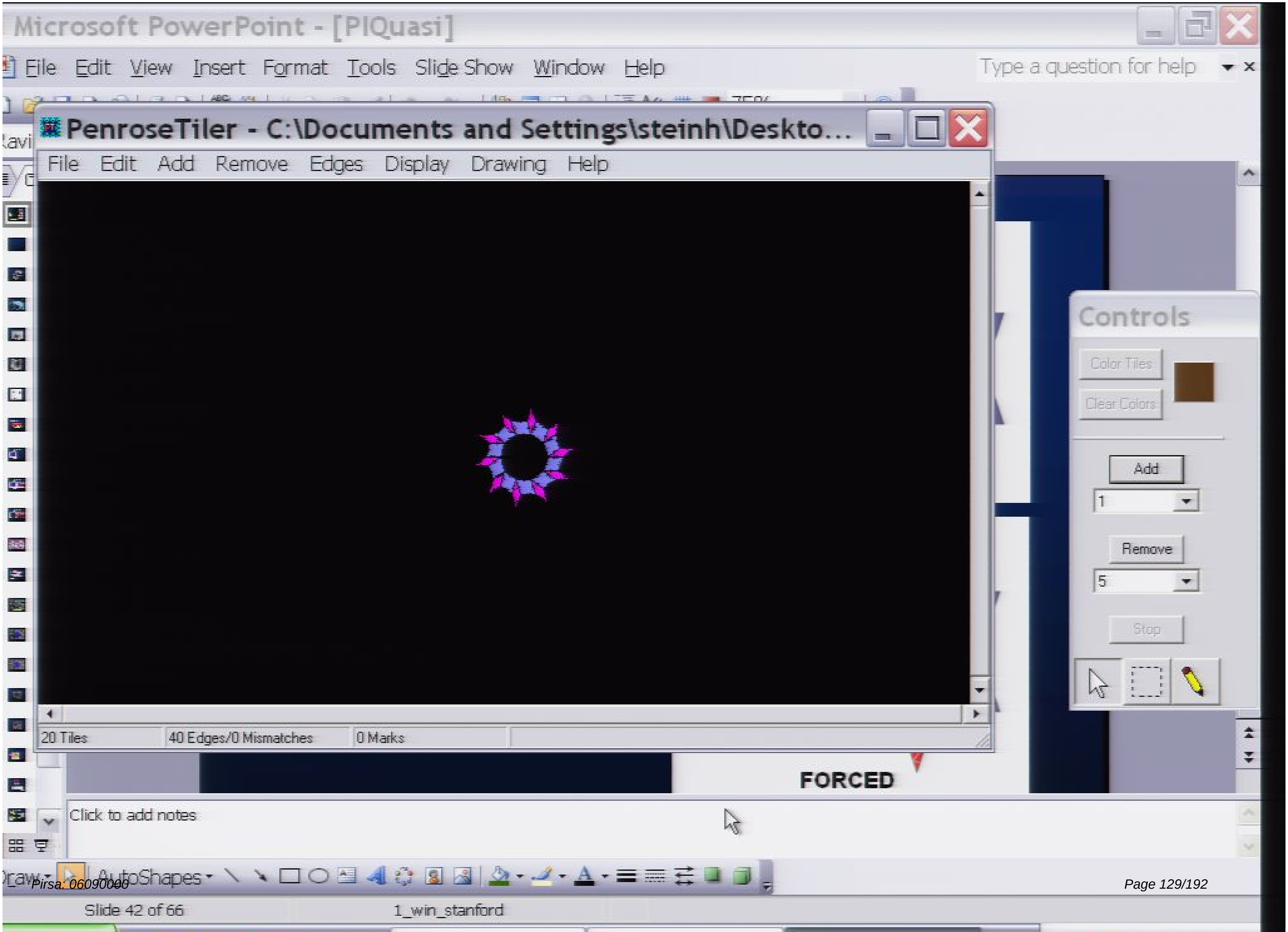
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20 Tiles
40 Edges/0 Mismatches
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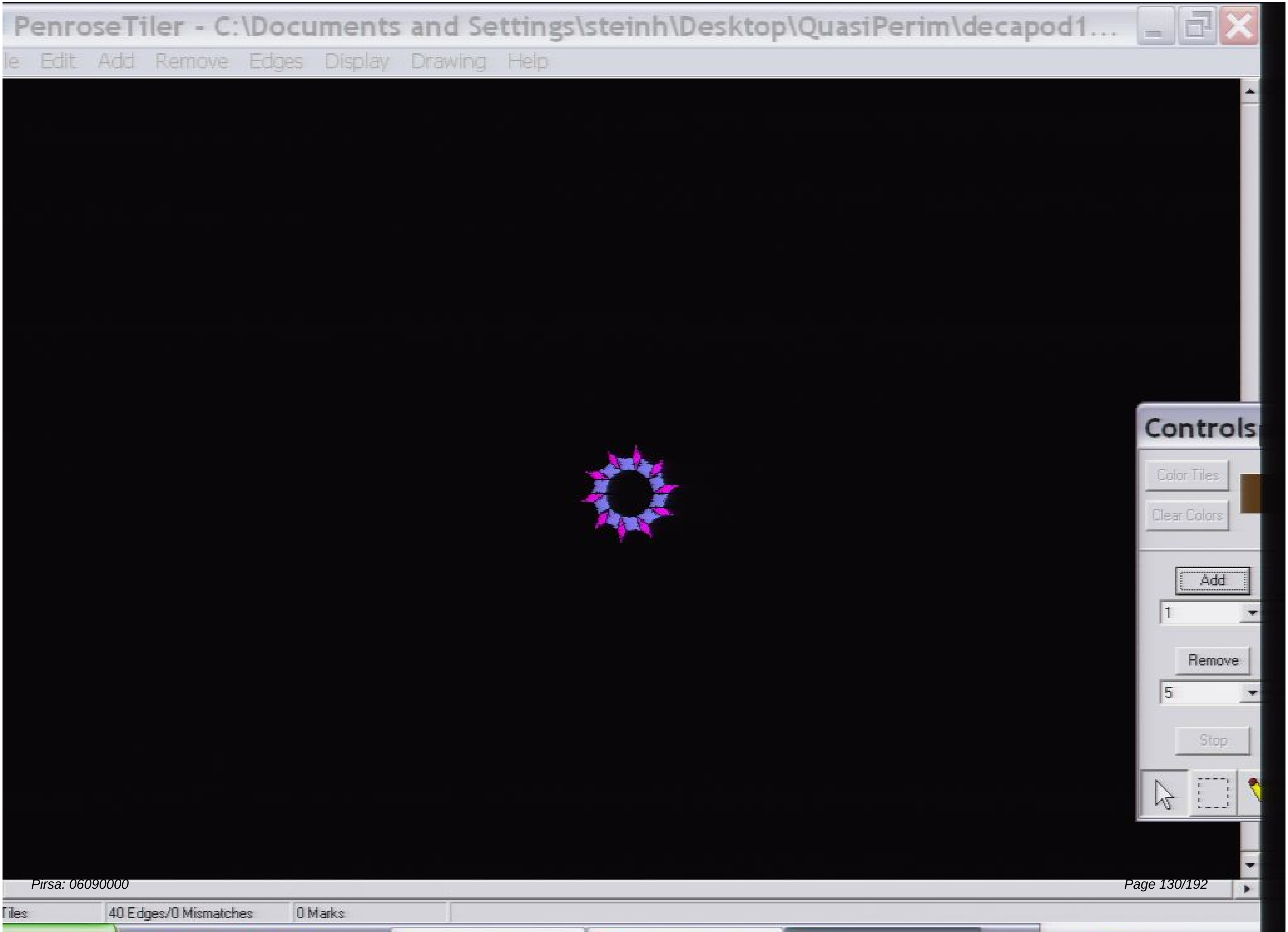
Click to add notes
AutoShapes
Slide 42 of 66
1_win_stanford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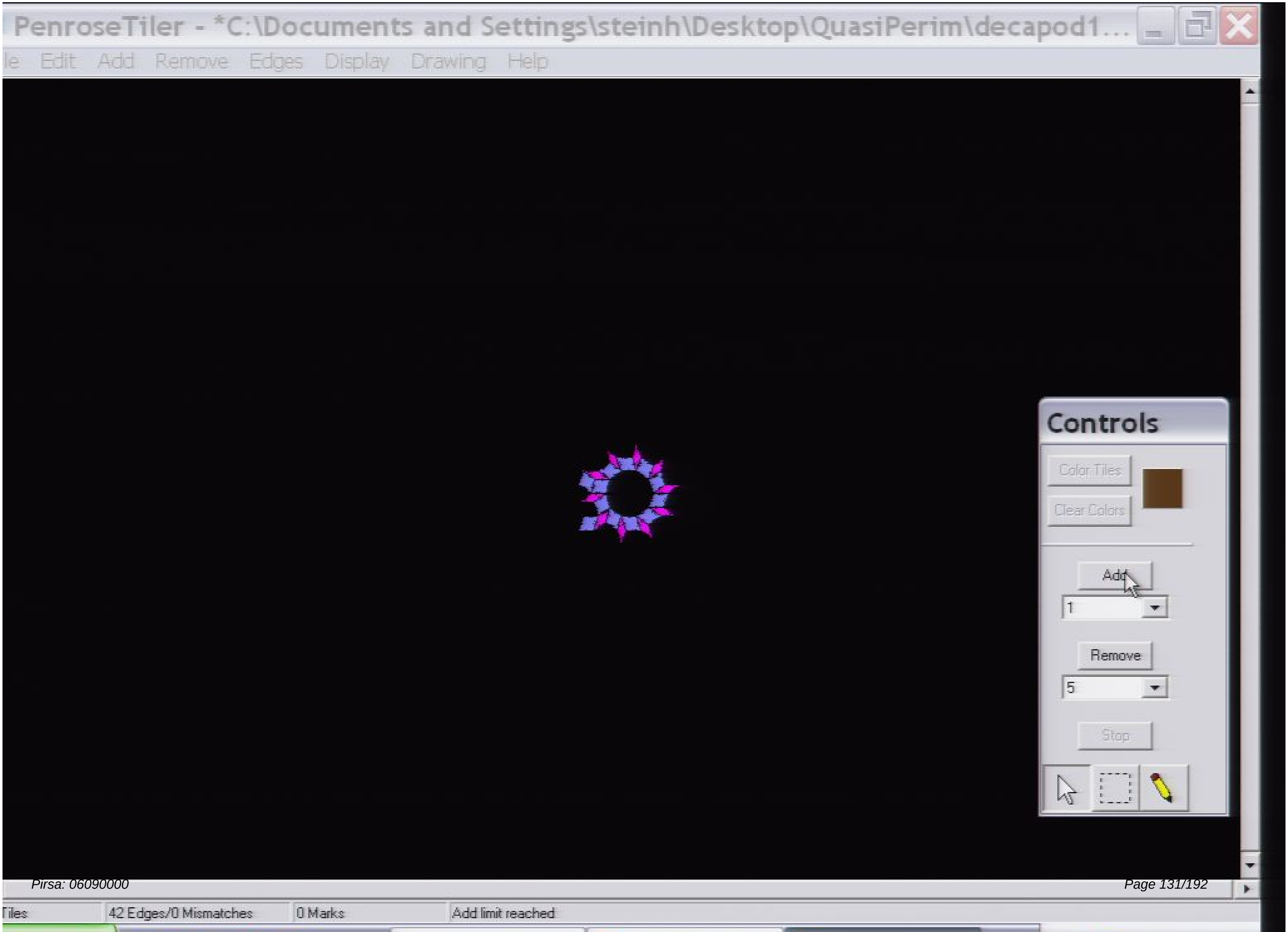
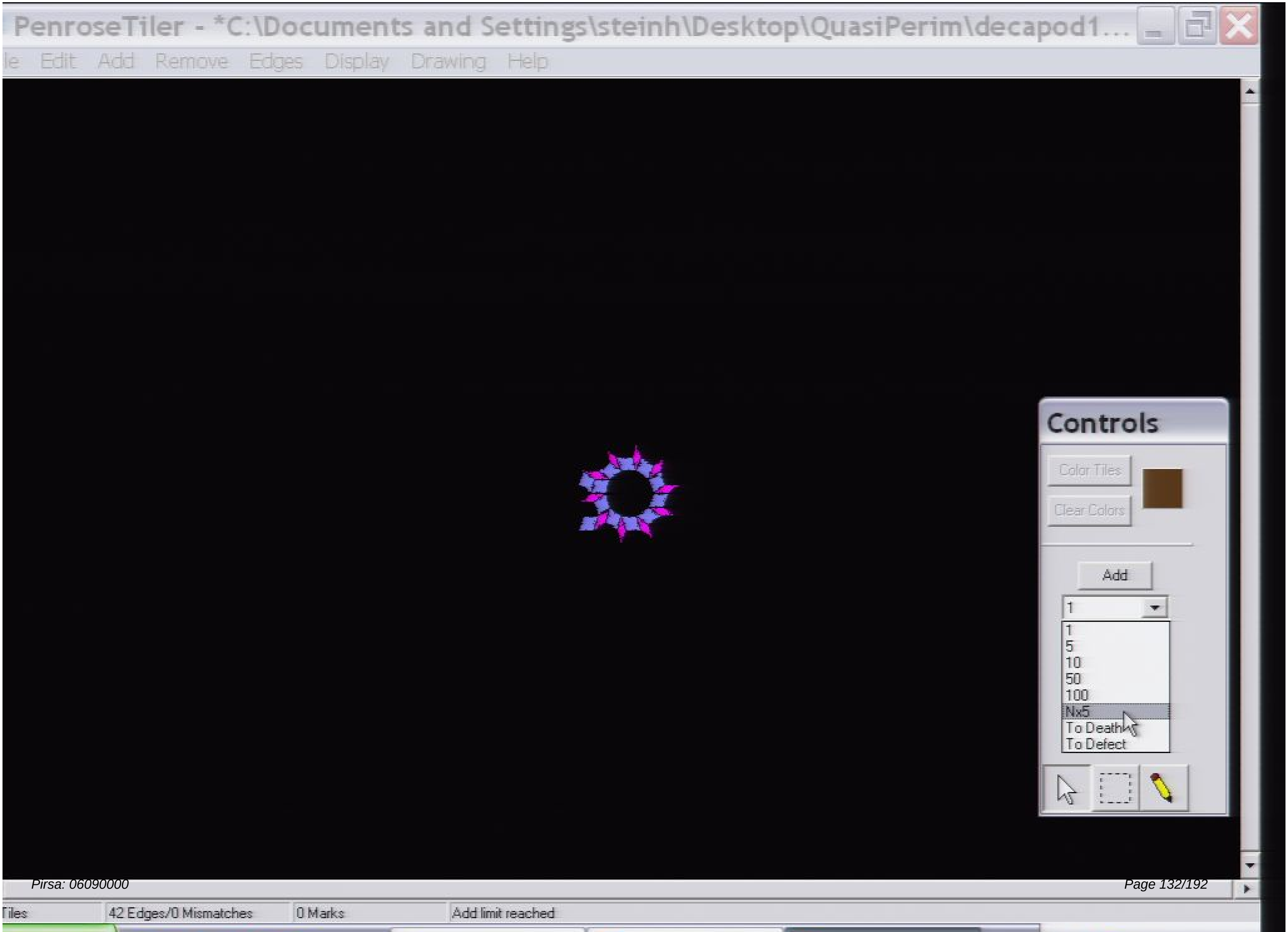
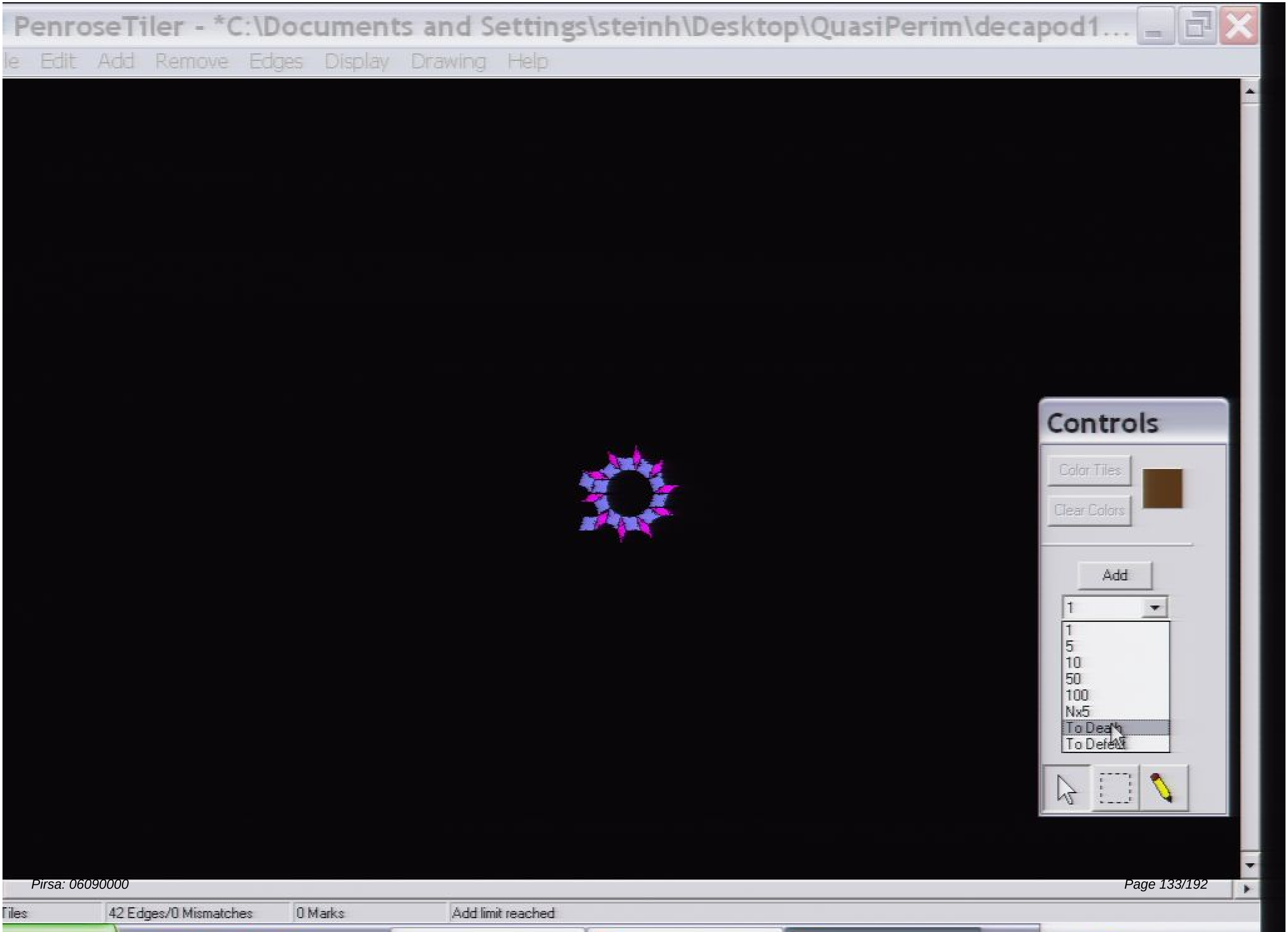
40 Edges/0 Mismatches
0 Marks



Tiles | 42 Edges/0 Mismatches | 0 Marks | Add limit reached



Tiles | 42 Edges/0 Mismatches | 0 Marks | Add limit reached



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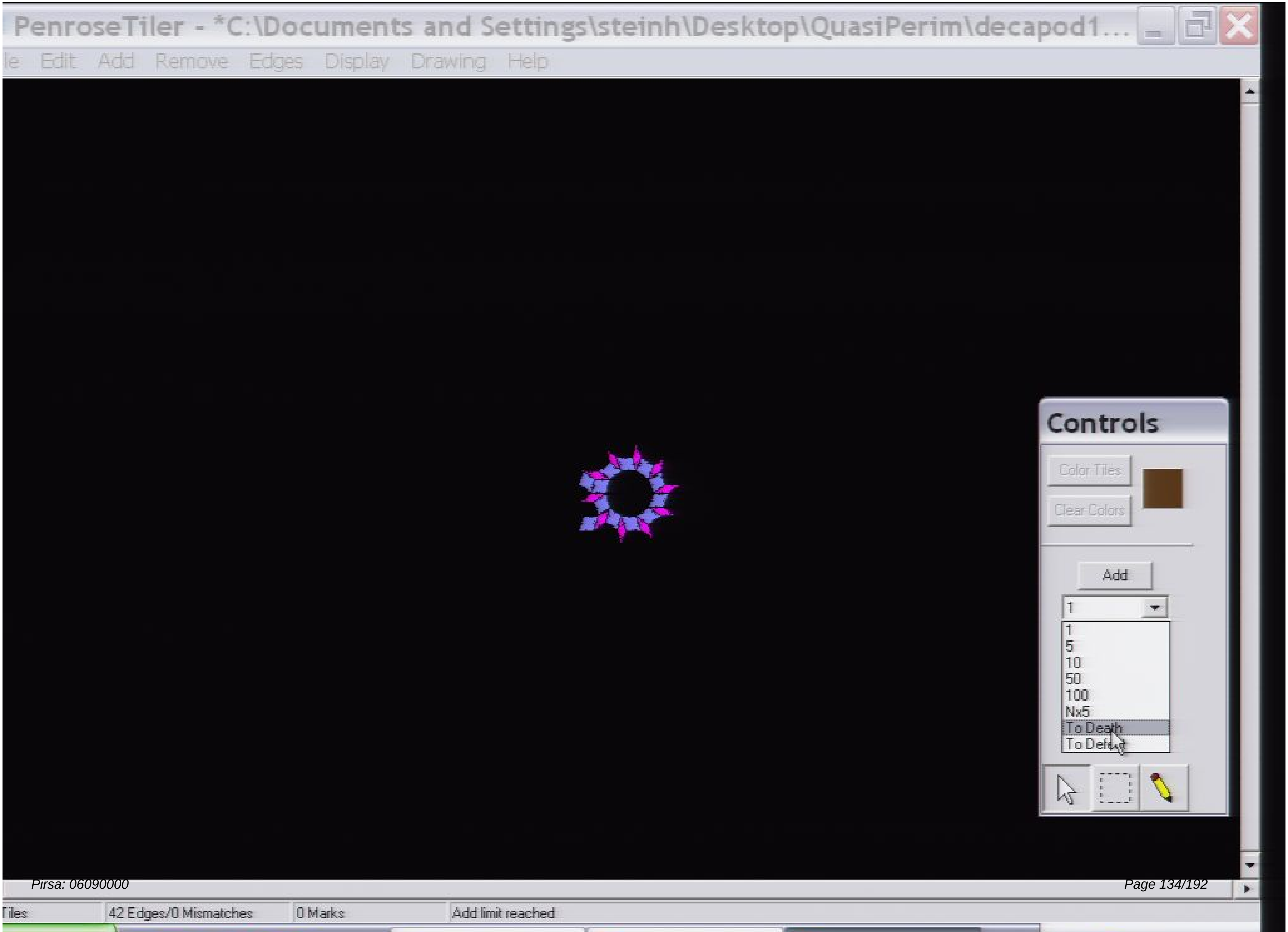
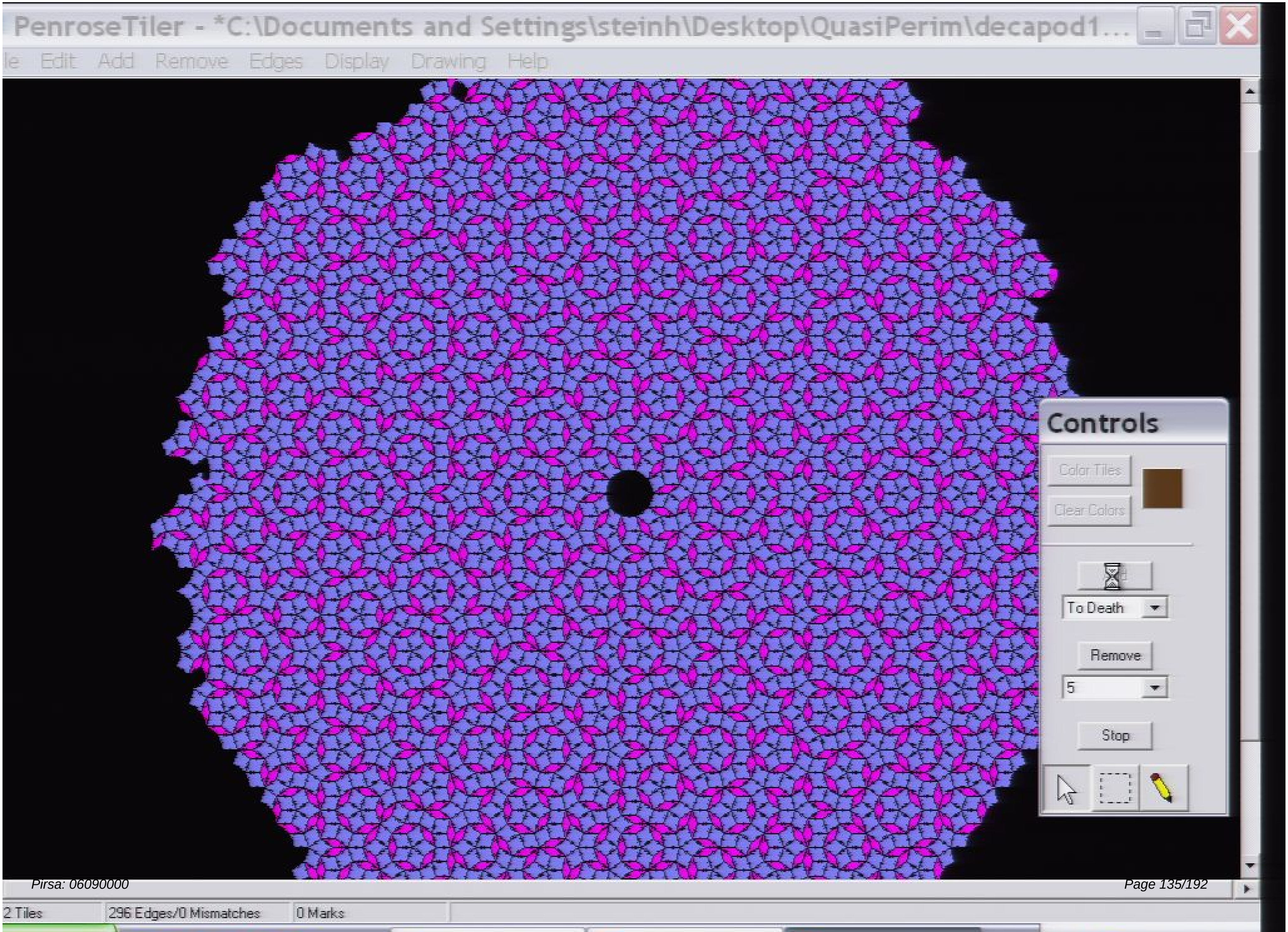
Tiles | 42 Edges/0 Mismatches | 0 Marks | Add limit reached



Tiles | 42 Edges/0 Mismatches | 0 Marks | Add limit reached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le Edit Add Remove Edges Display Drawing Help
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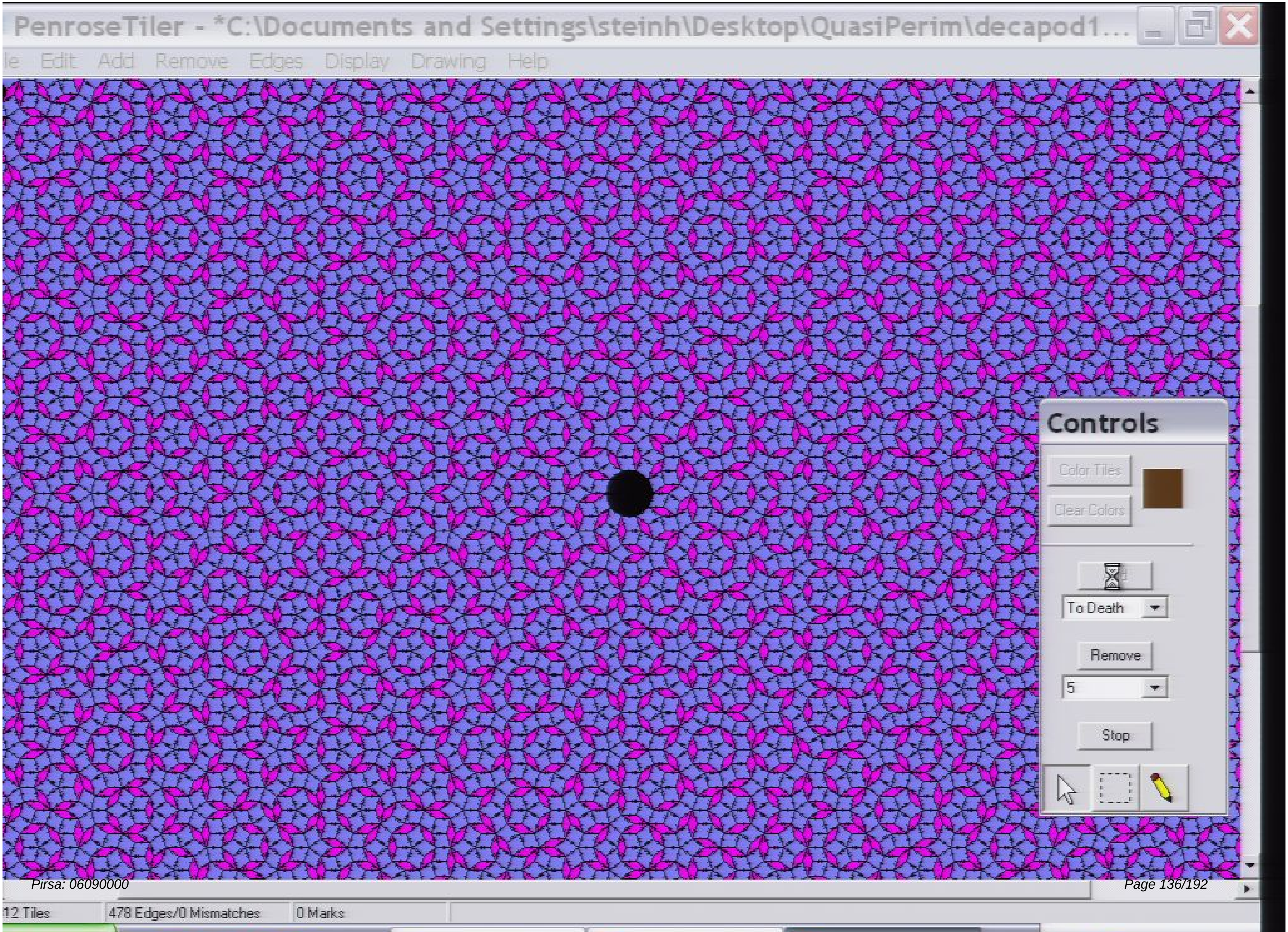
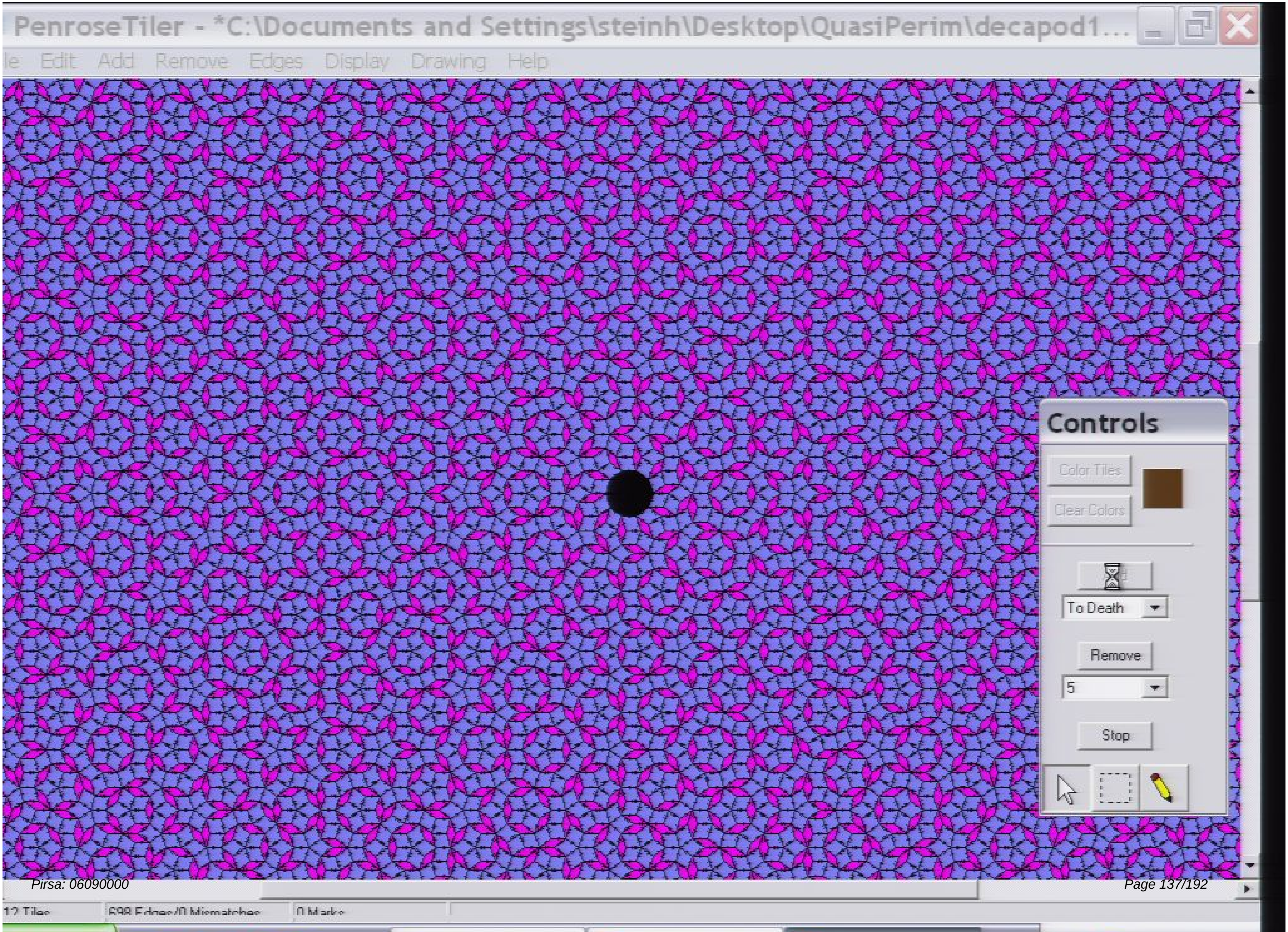
2 Tiles
296 Edges/0 Mismatches
0 Marks



12 Tiles

478 Edges/0 Mismatches

0 Marks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le
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Clear Colors
To Death
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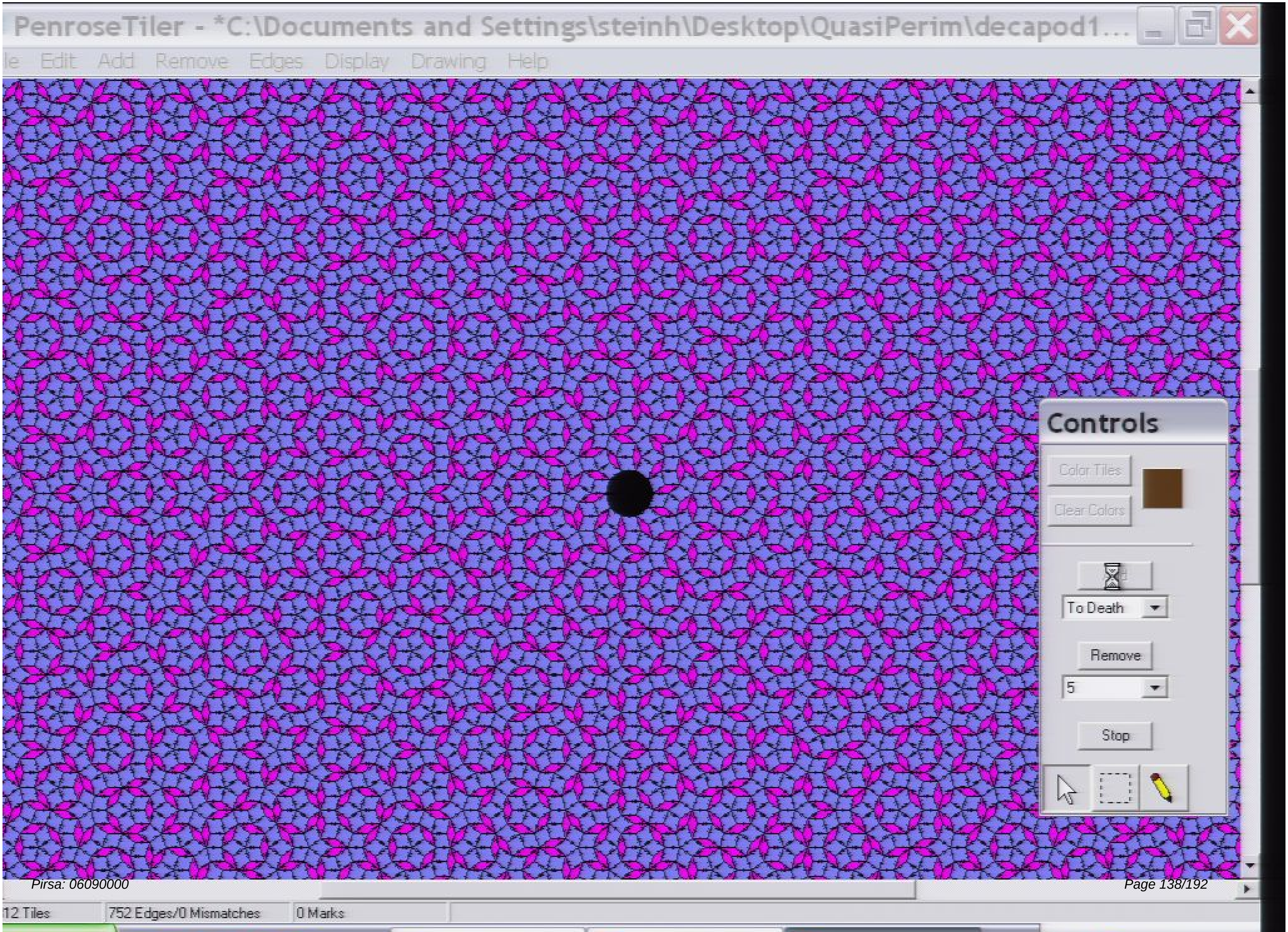
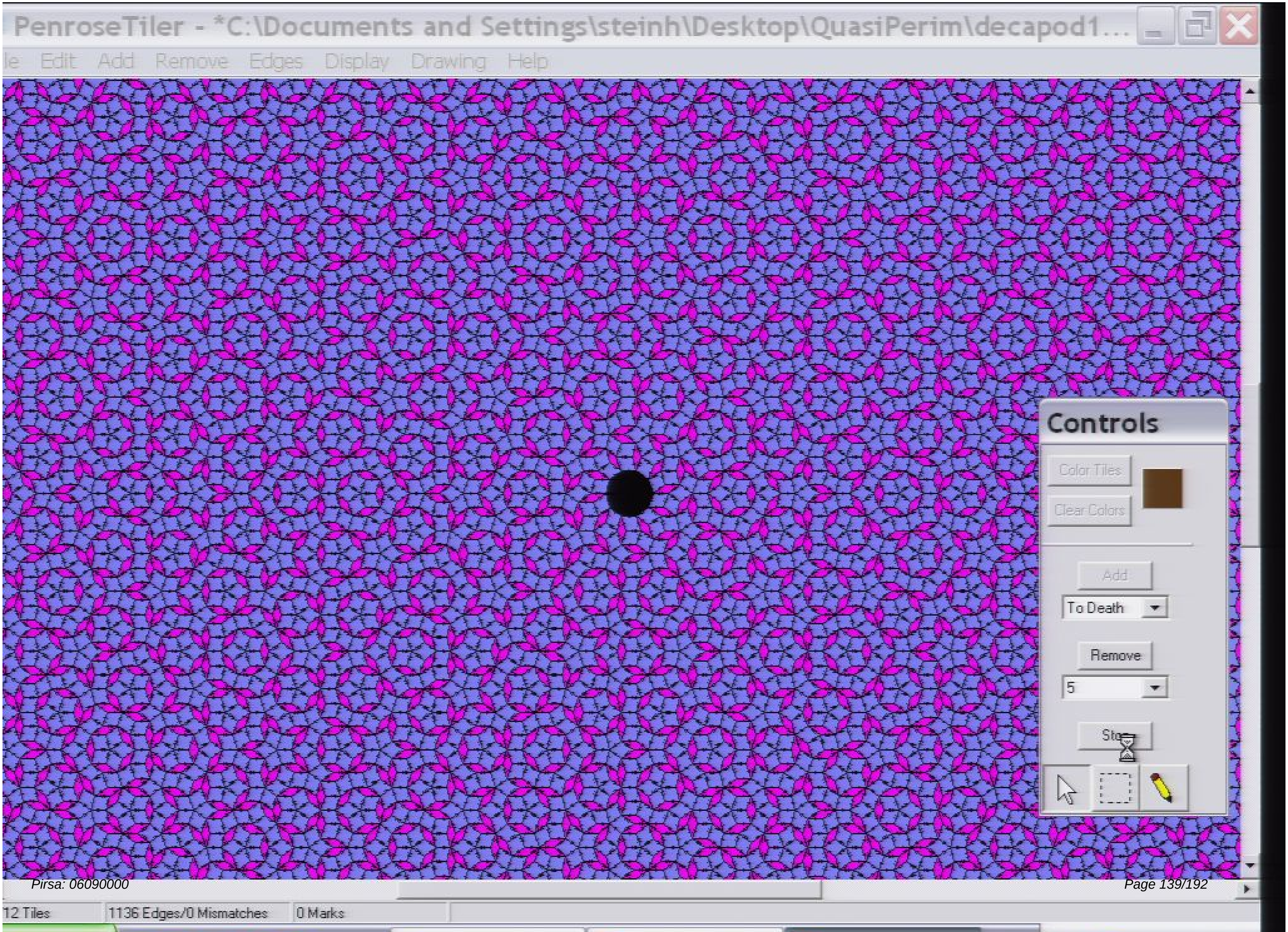
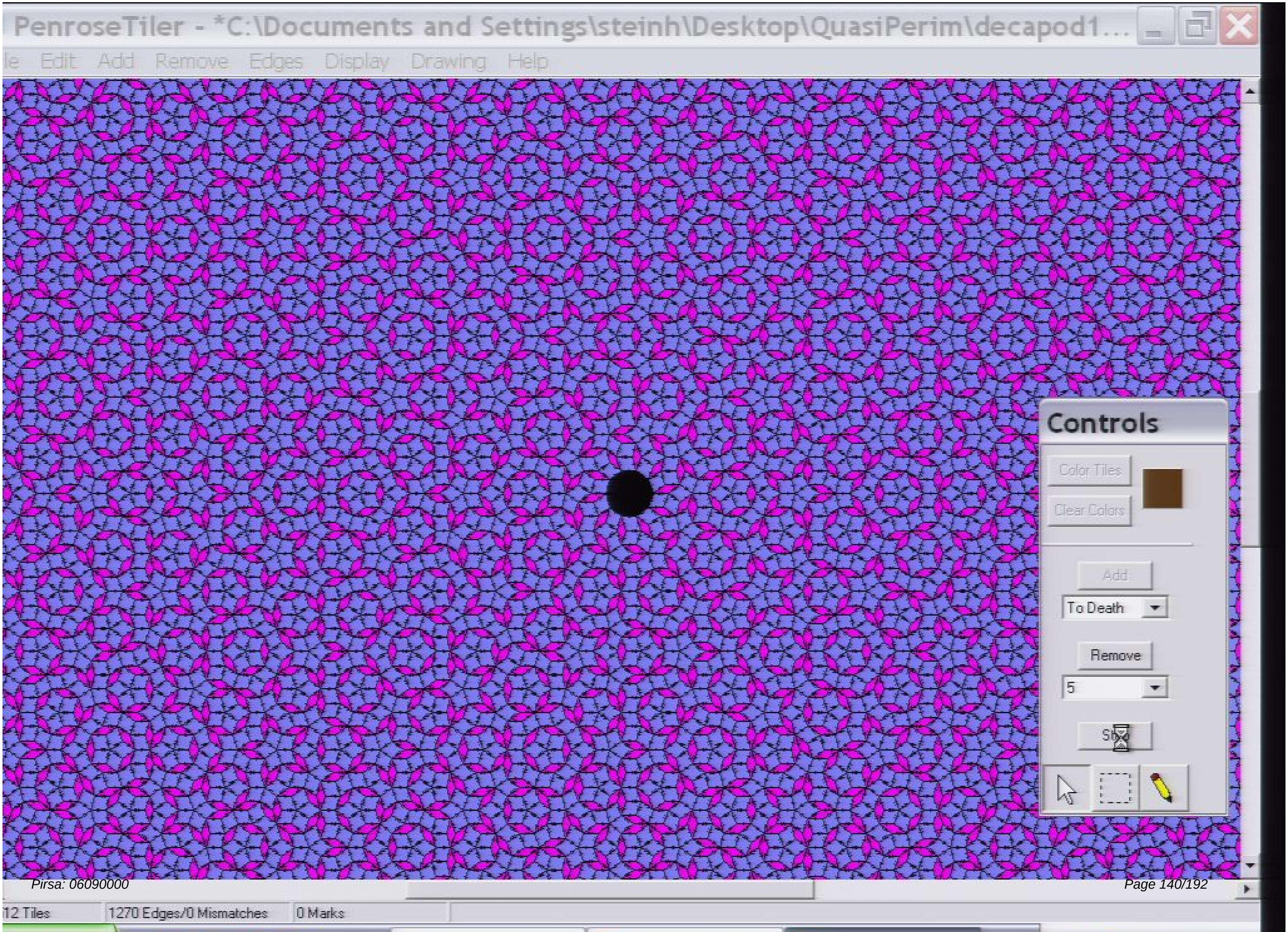
5
Stop
12 Tiles
698 Edges/0 Mismatches
0 Marks



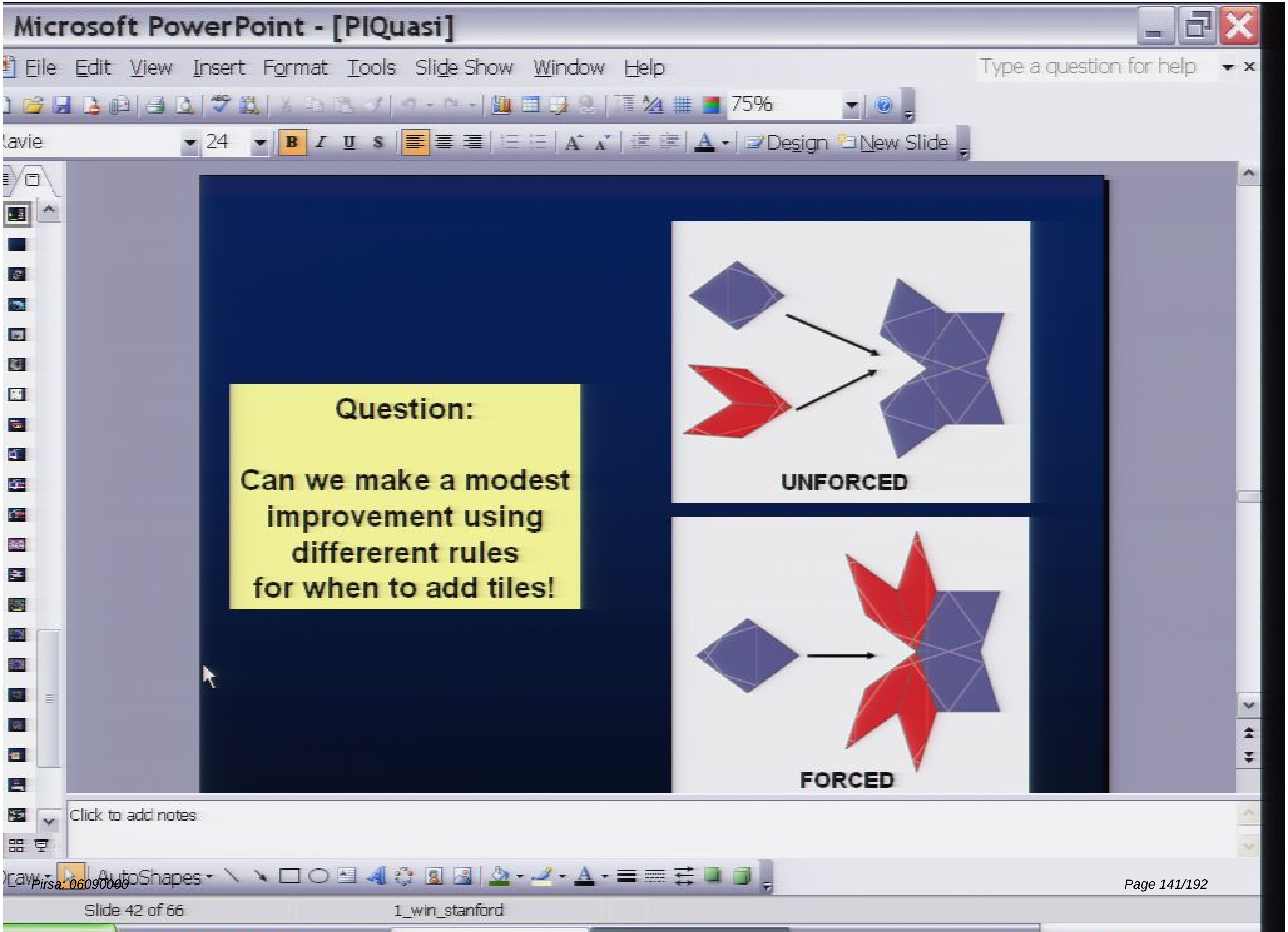
12 Tiles | 752 Edges/0 Mismatches | 0 Marks



12 Tiles | 1136 Edges/0 Mismatches | 0 Marks



12 Tiles | 1270 Edges/0 Mismatches | 0 Marks



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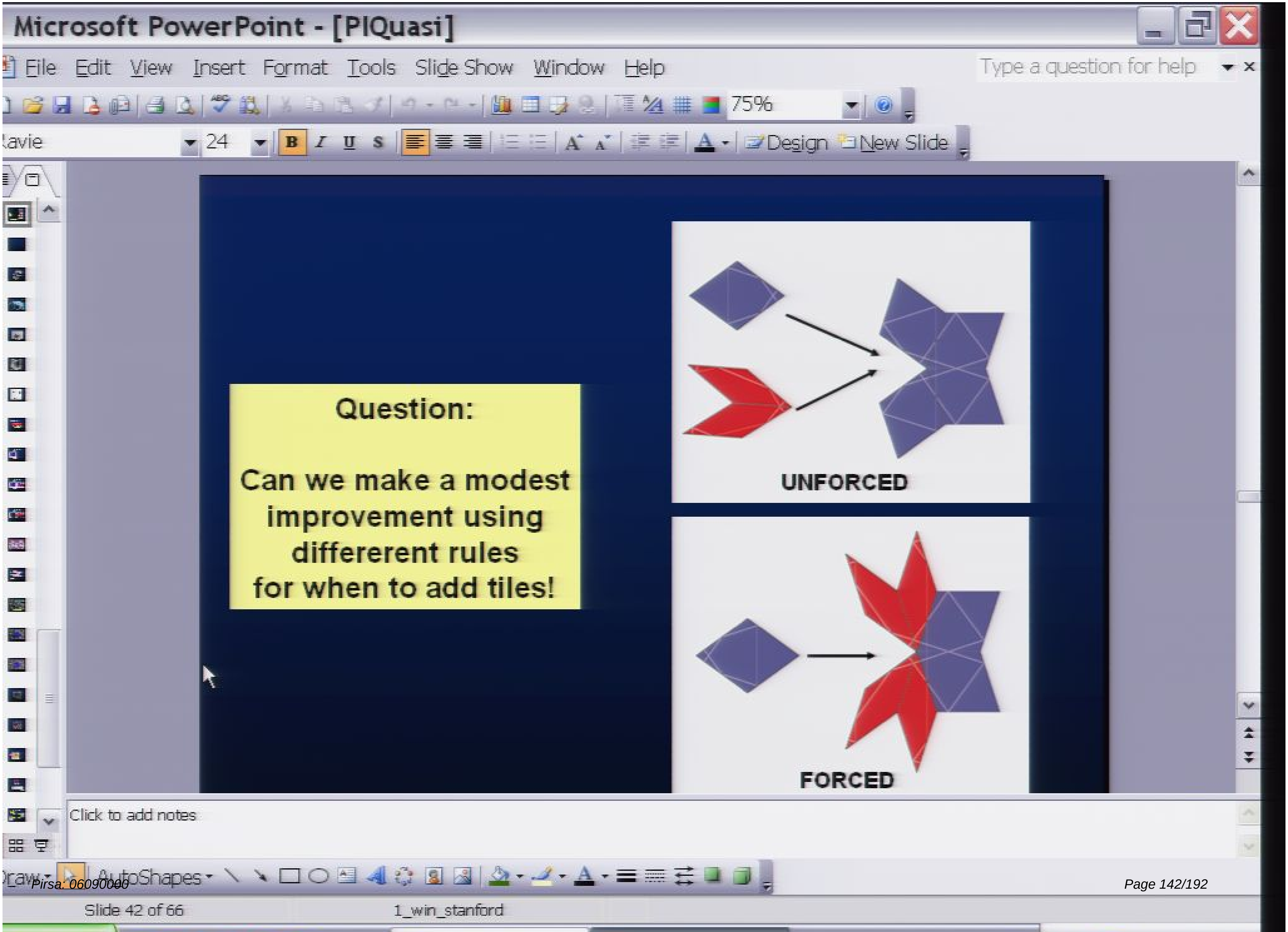

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Click to add notes

Slide 42 of 66

1_win_stanford

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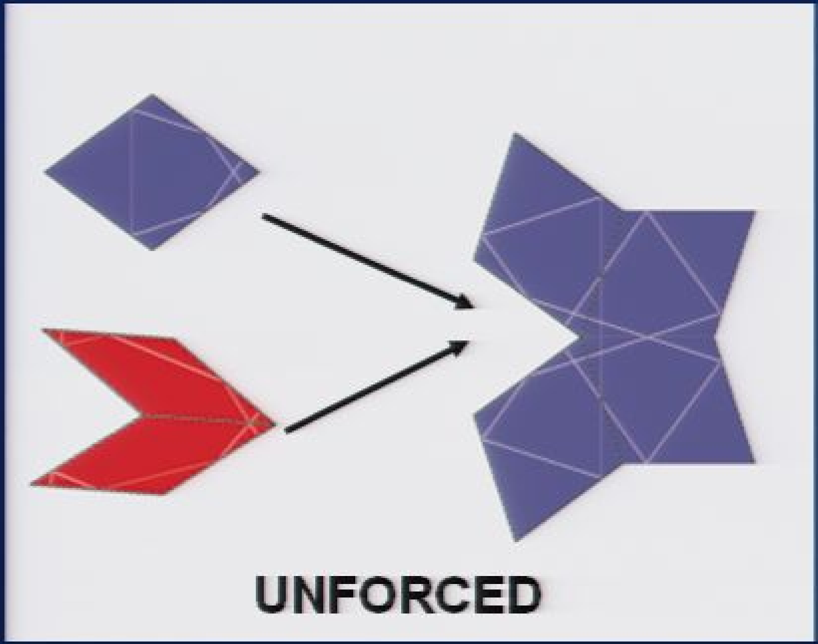

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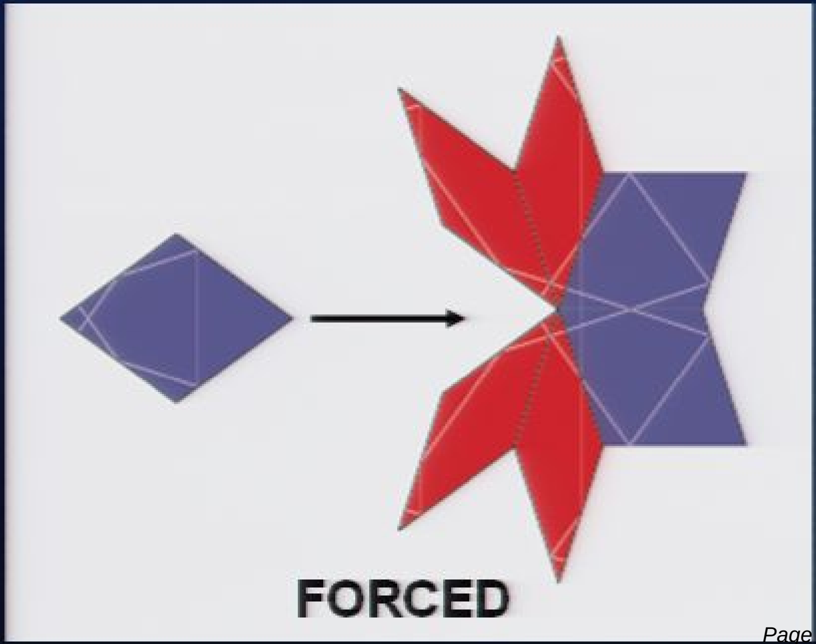

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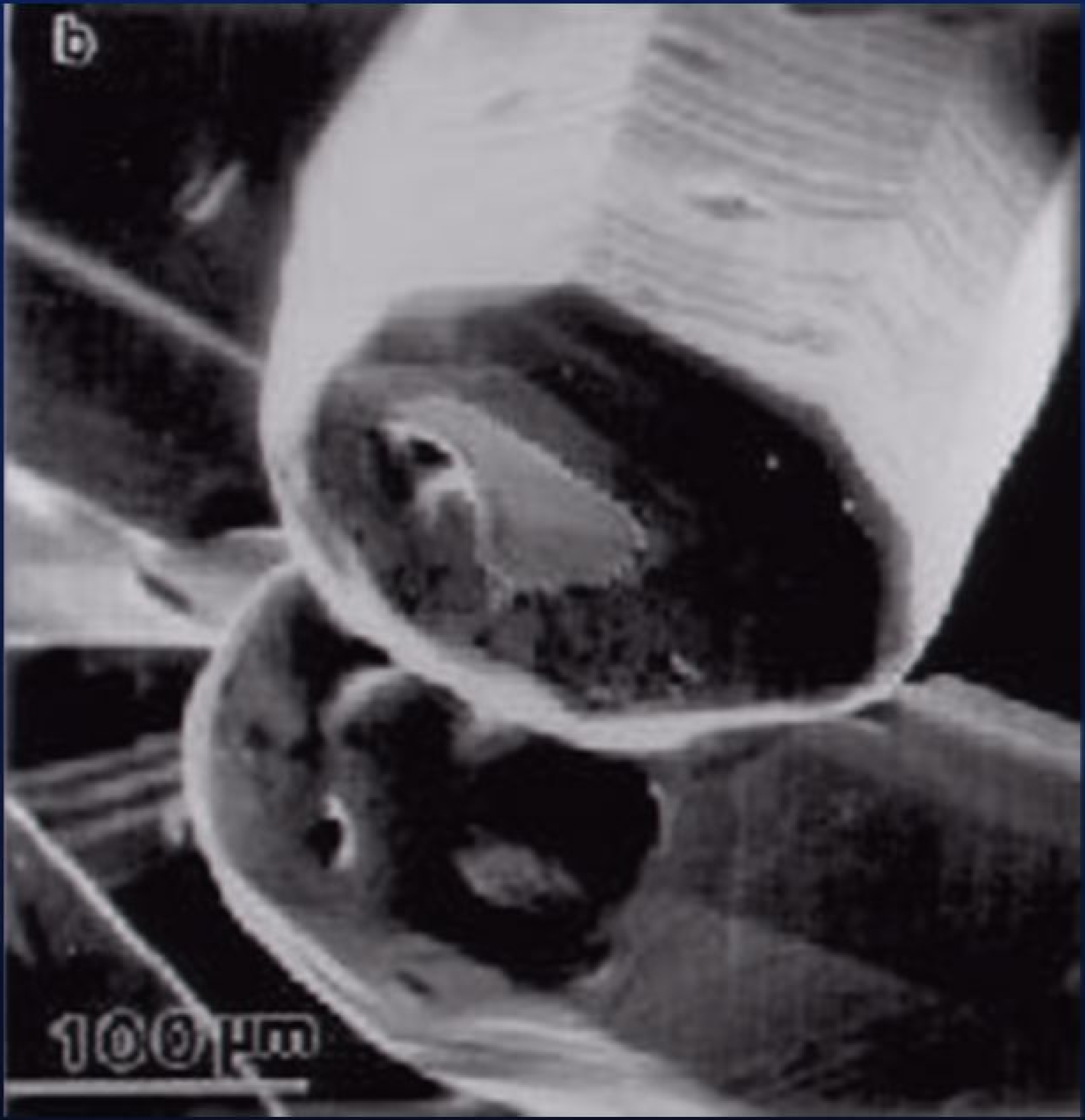
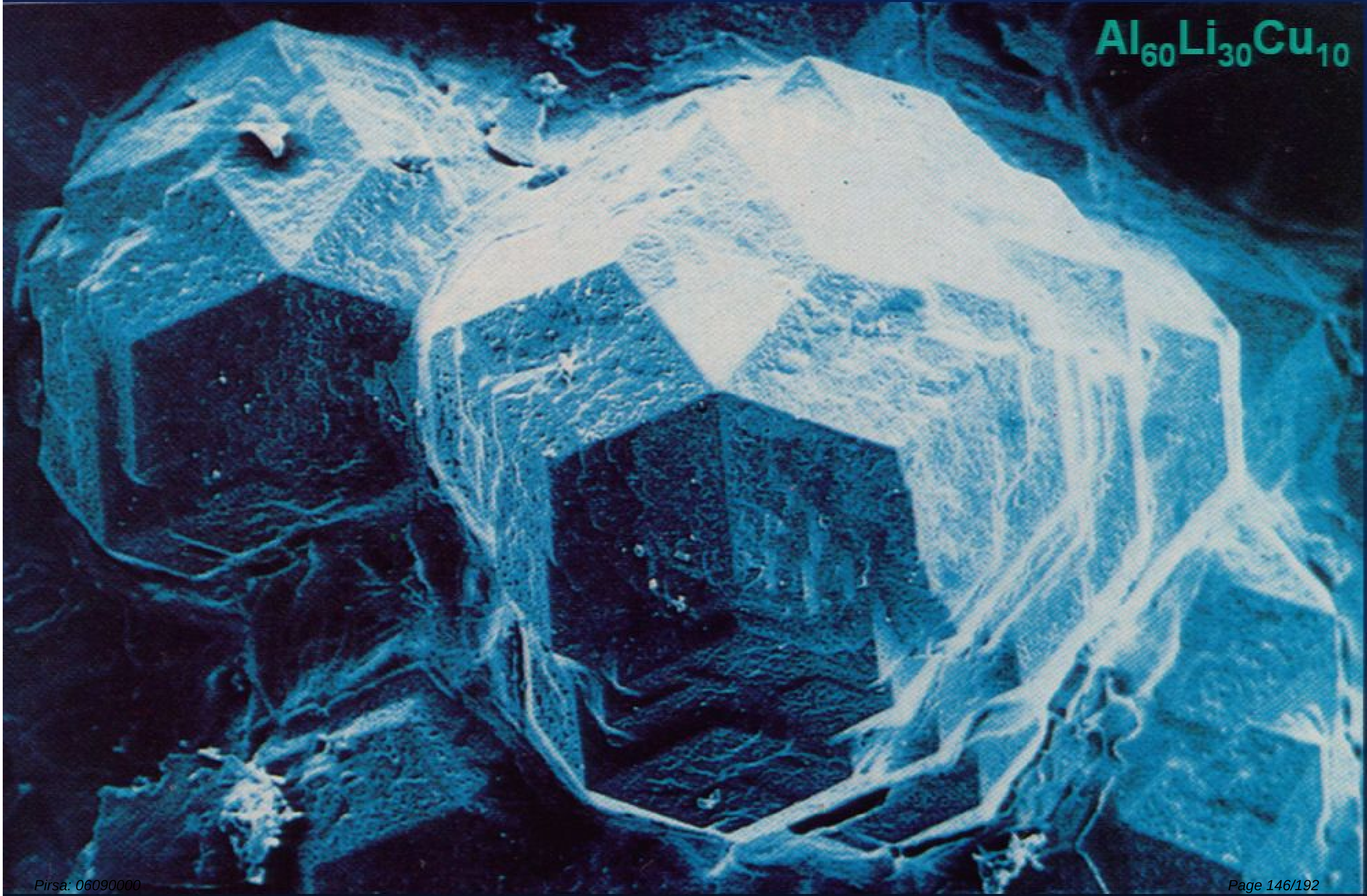
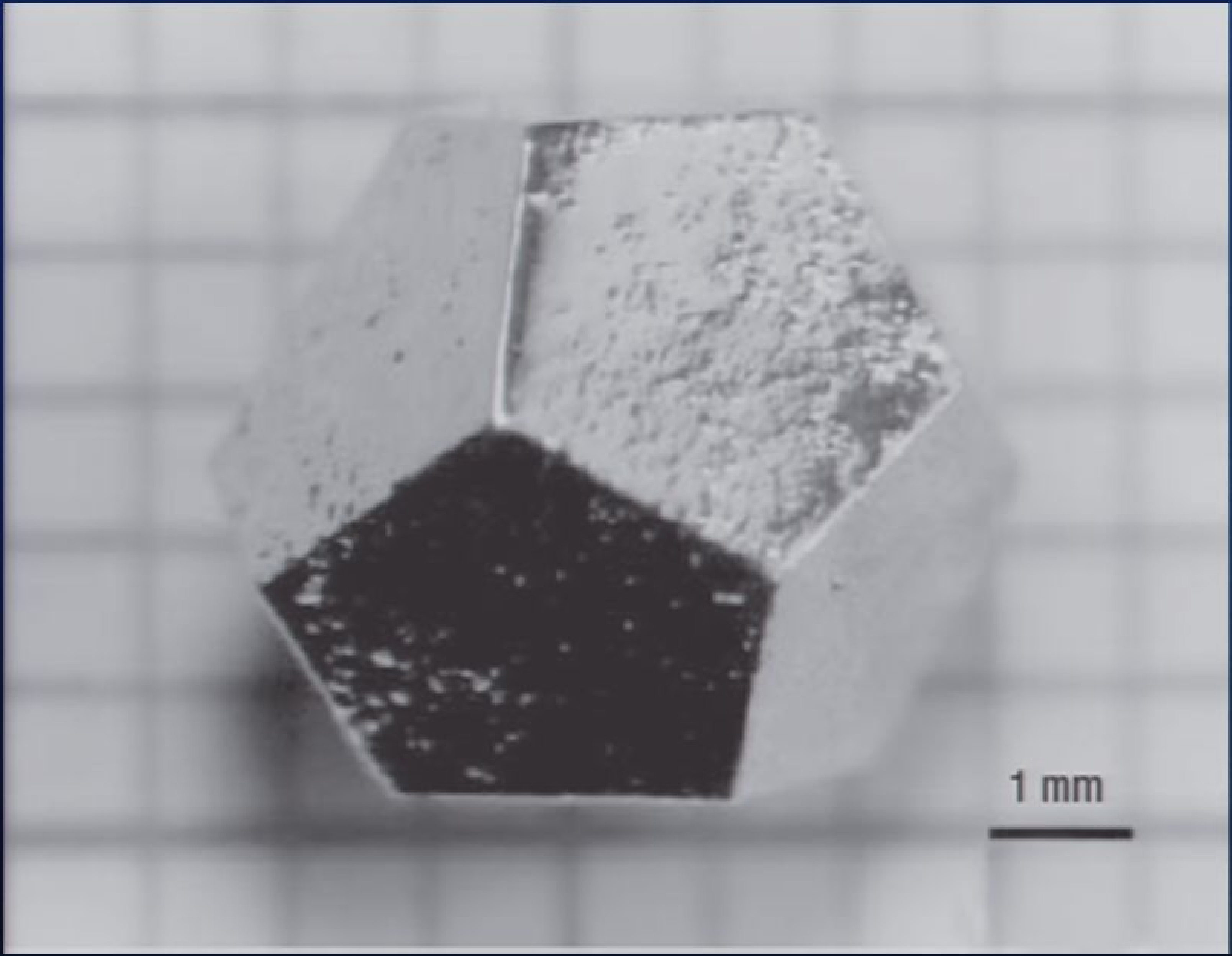


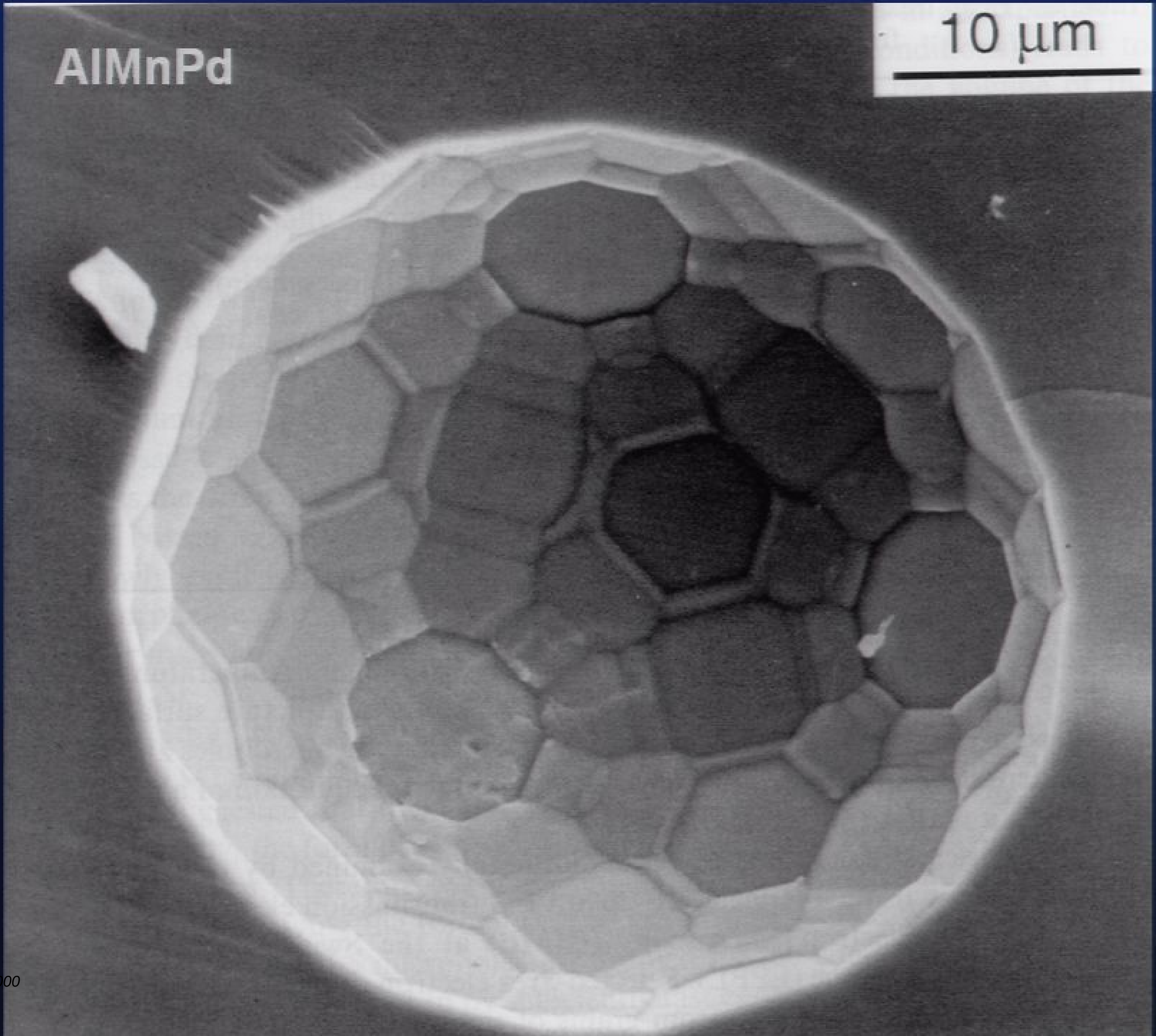
$Al_{70}\ Ni_{15}\ Co_{15}$

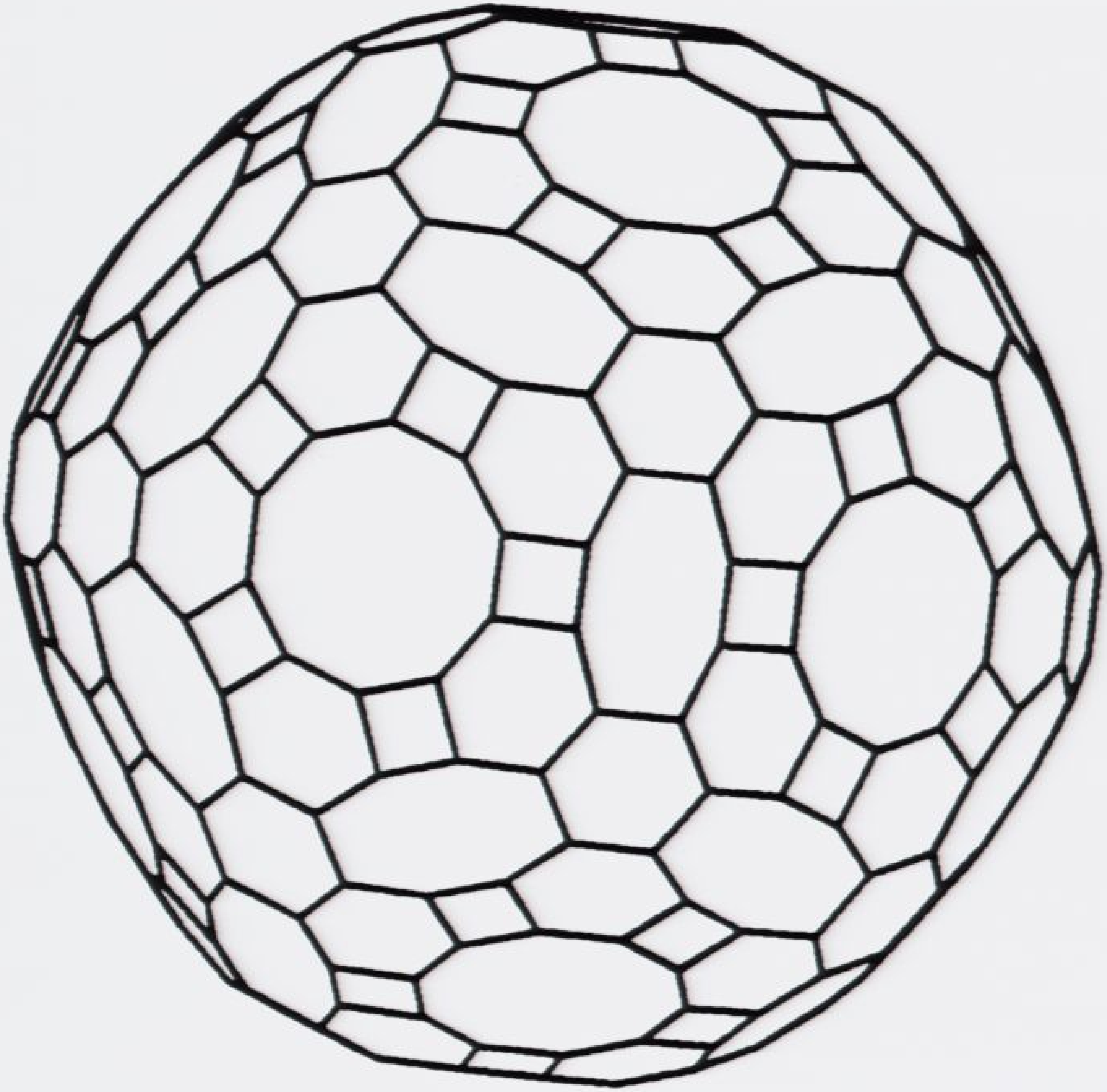


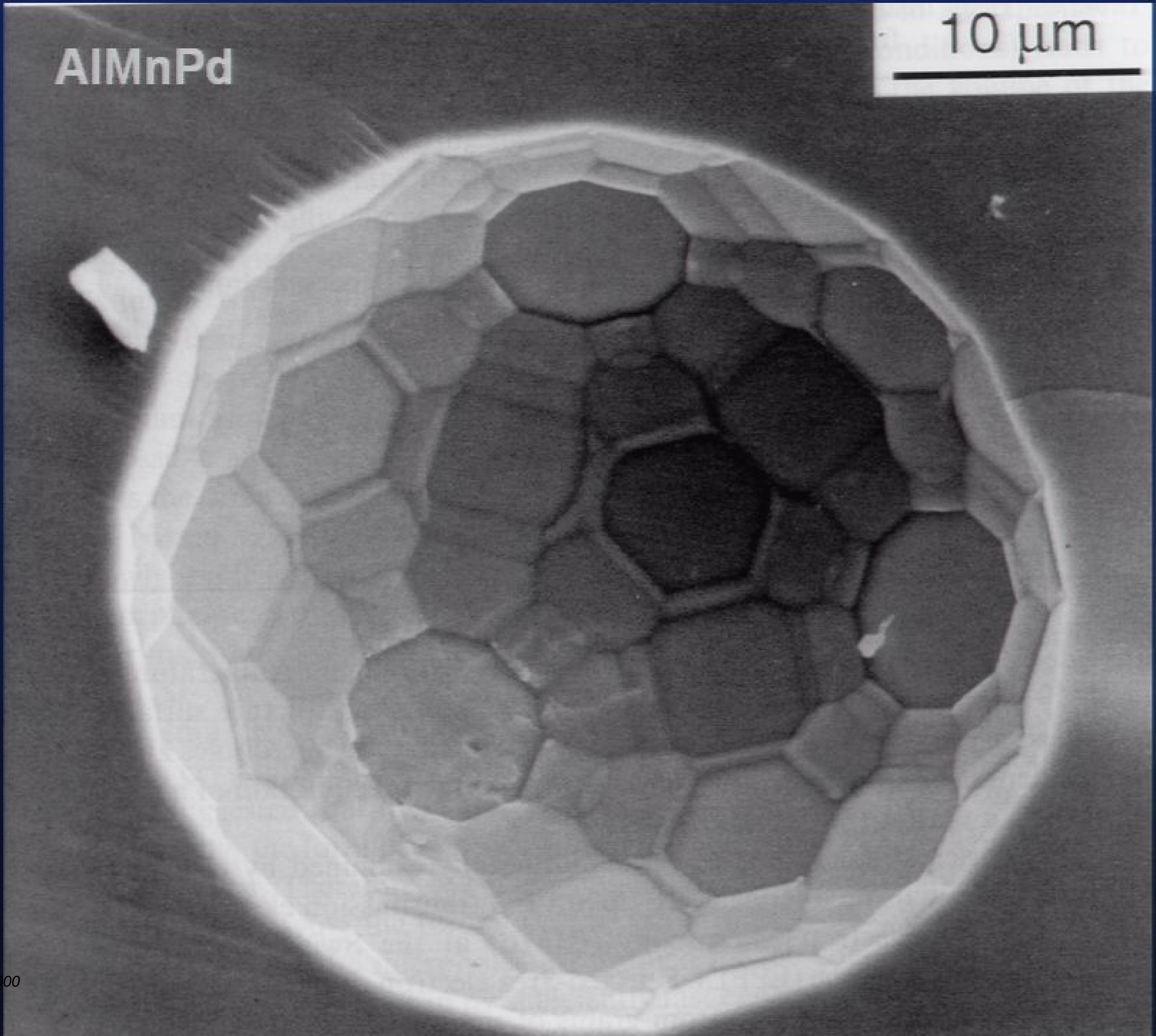
$Al_{60}Li_{30}Cu_{10}$



$Zn_{56.8}\ Mg_{34.6}\ Ho_{8.7}$


AlMnPd
10 μm

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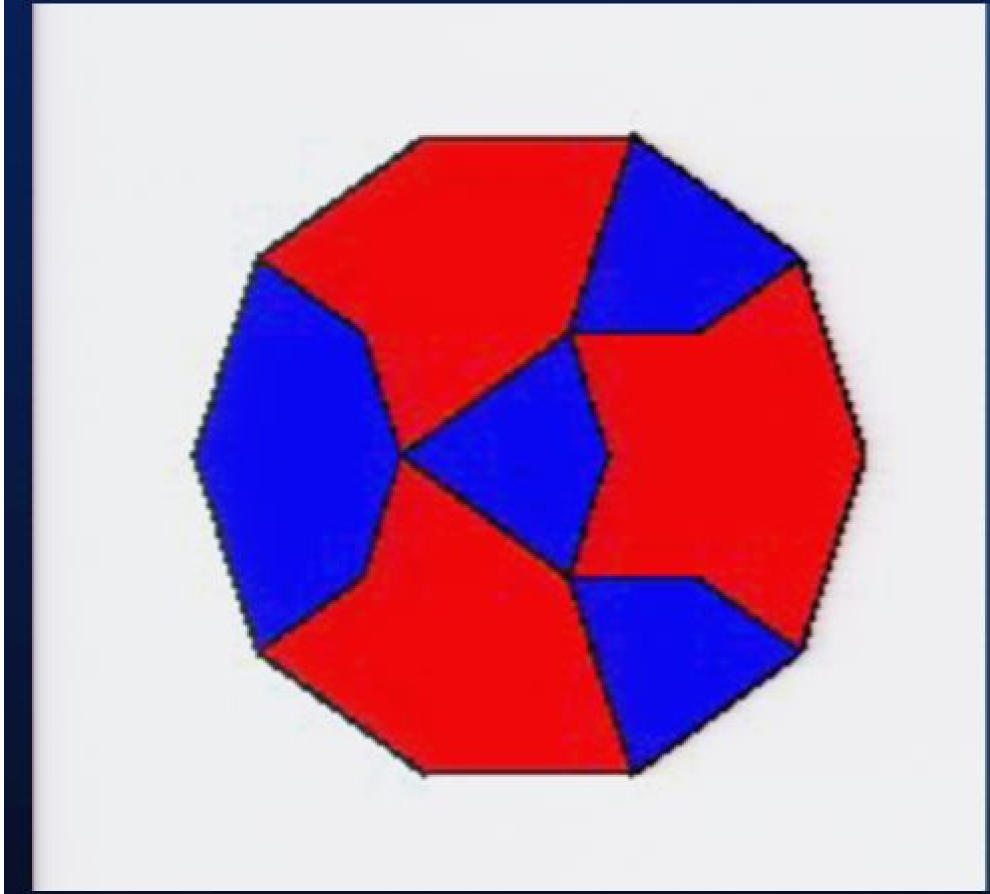
Quasi-unit Cell Picture

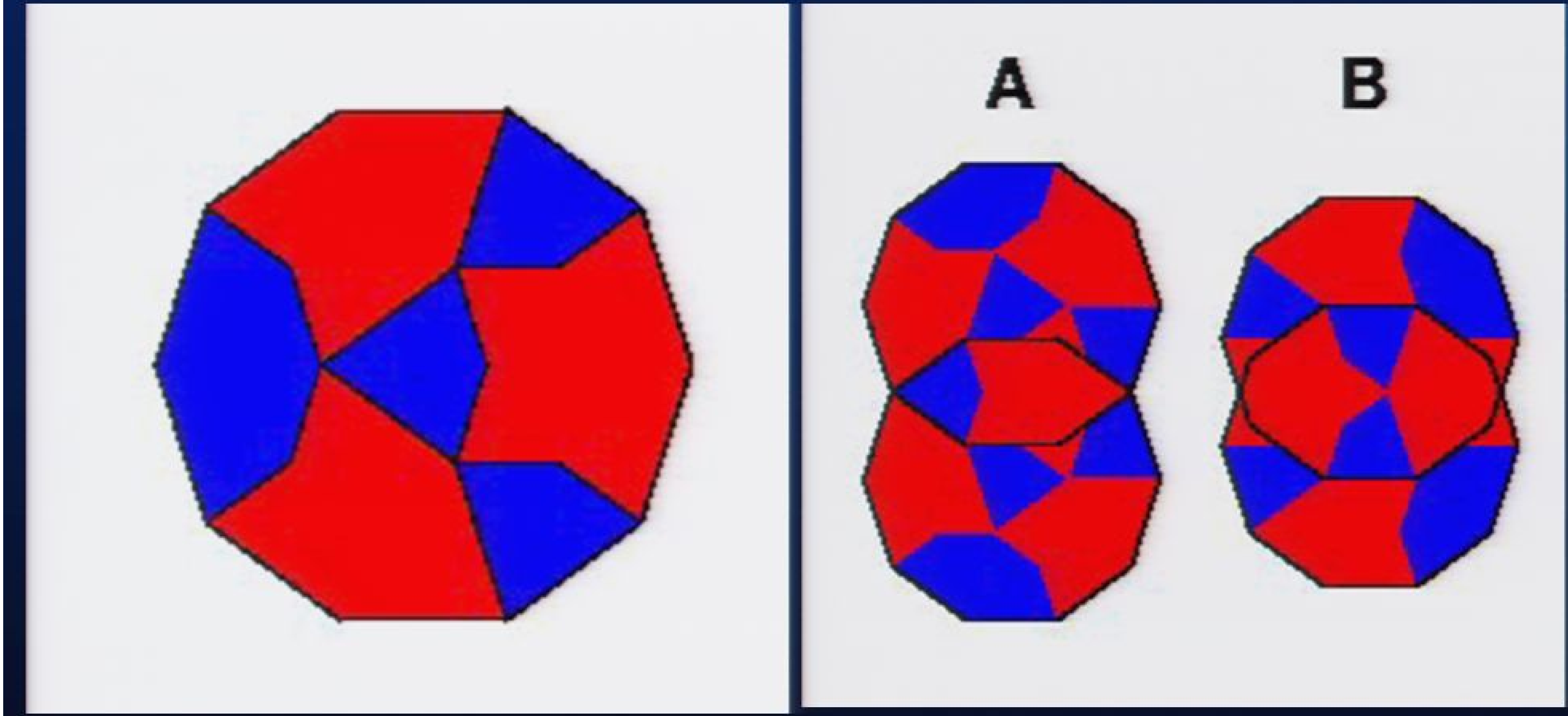
Gummelt Tile



P.J. Steinhardt, H.-C. Jeong (1996)

Quasi-unit Cell Picture

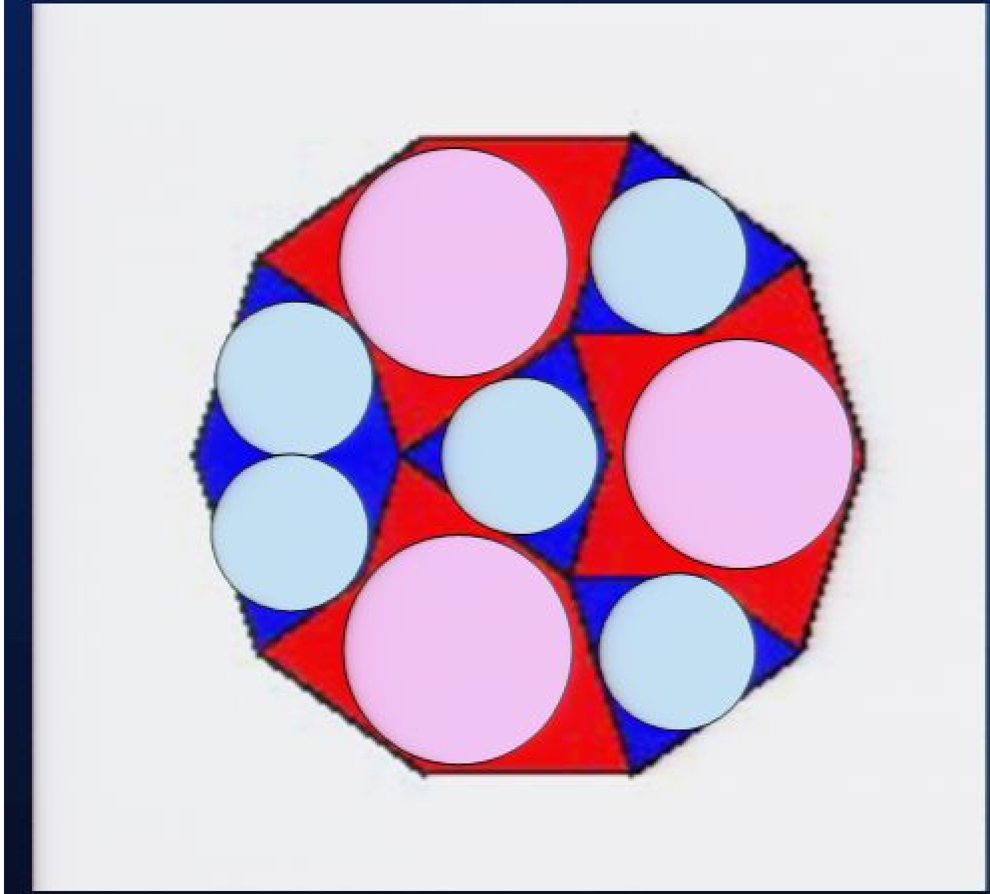
Gummelt Tile

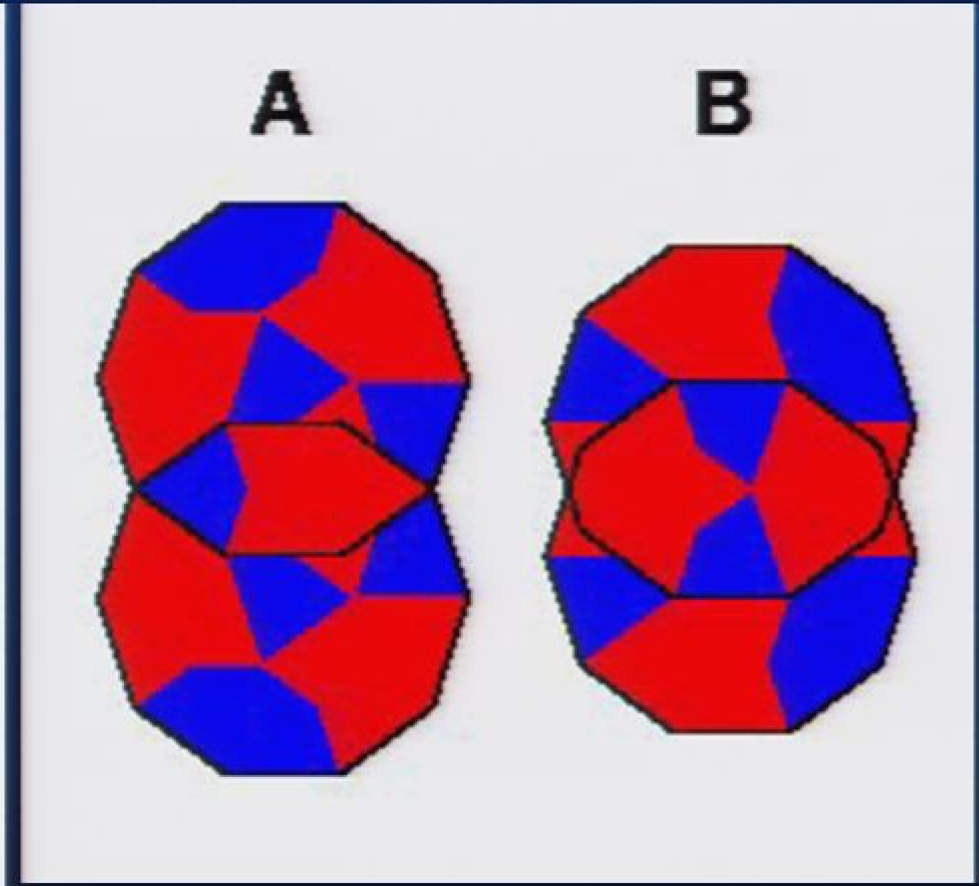


P.J. Steinhardt, H.-C. Jeong (1996)

Quasi-unit Cell Picture

Gummelt Tile





Quasi-unit Cell Picture

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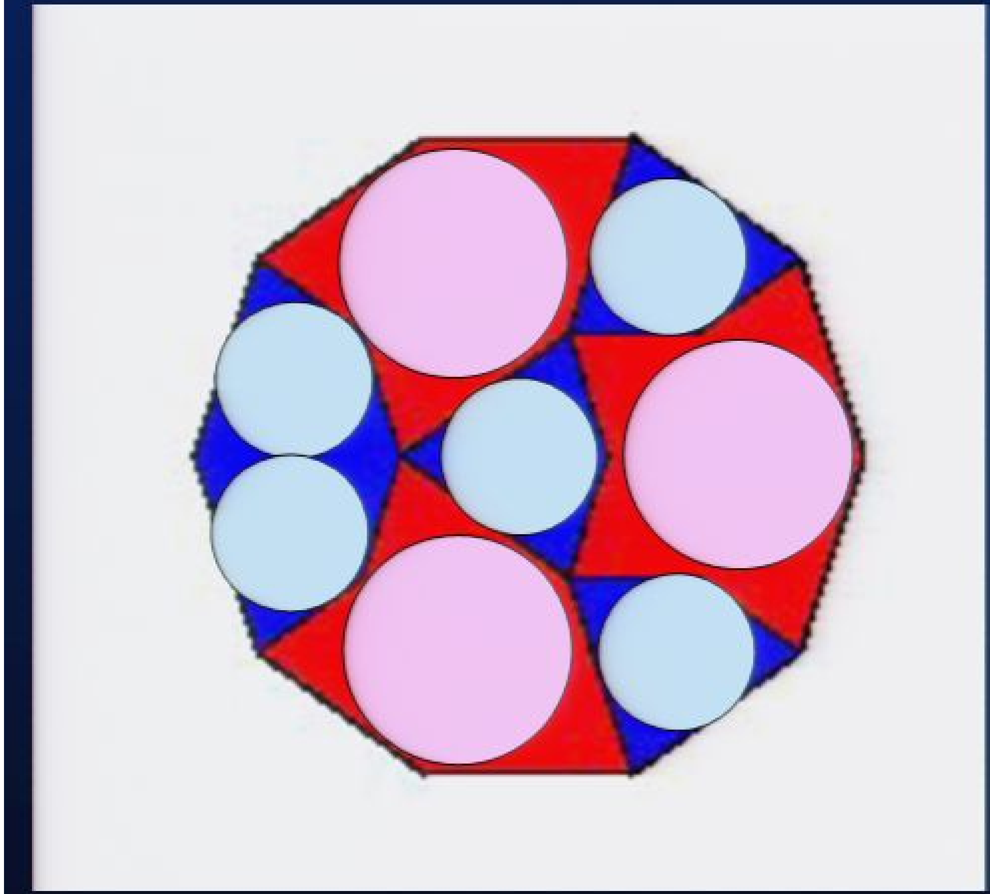
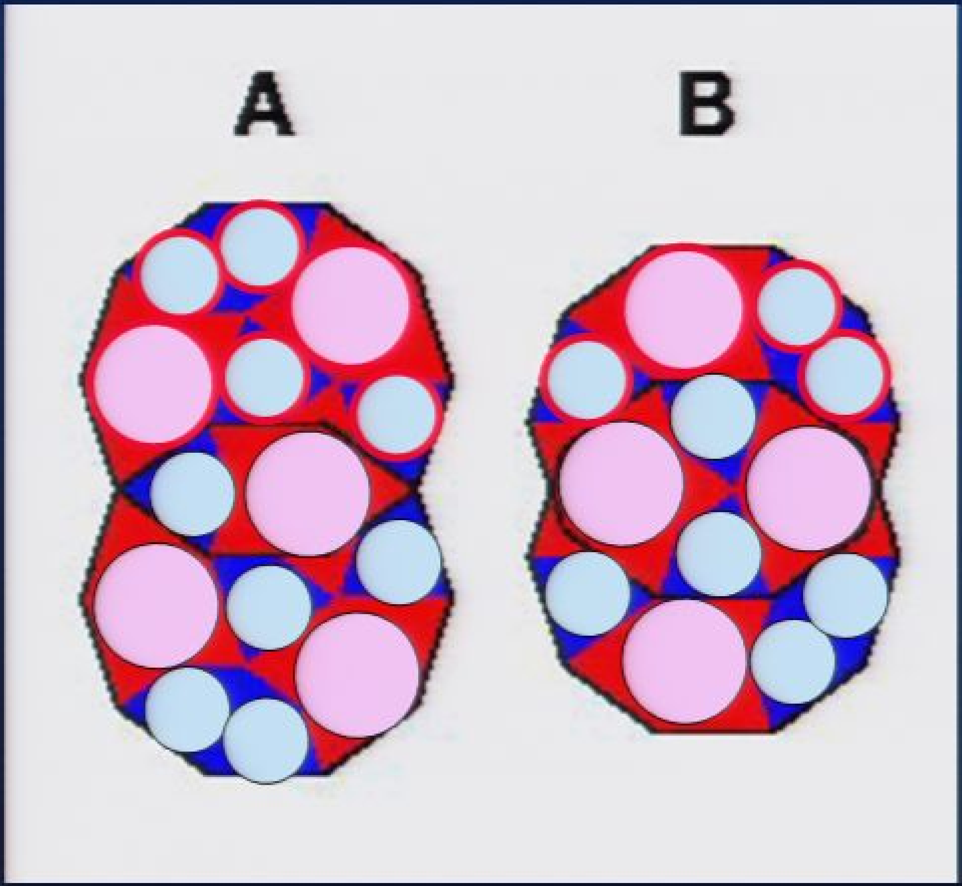
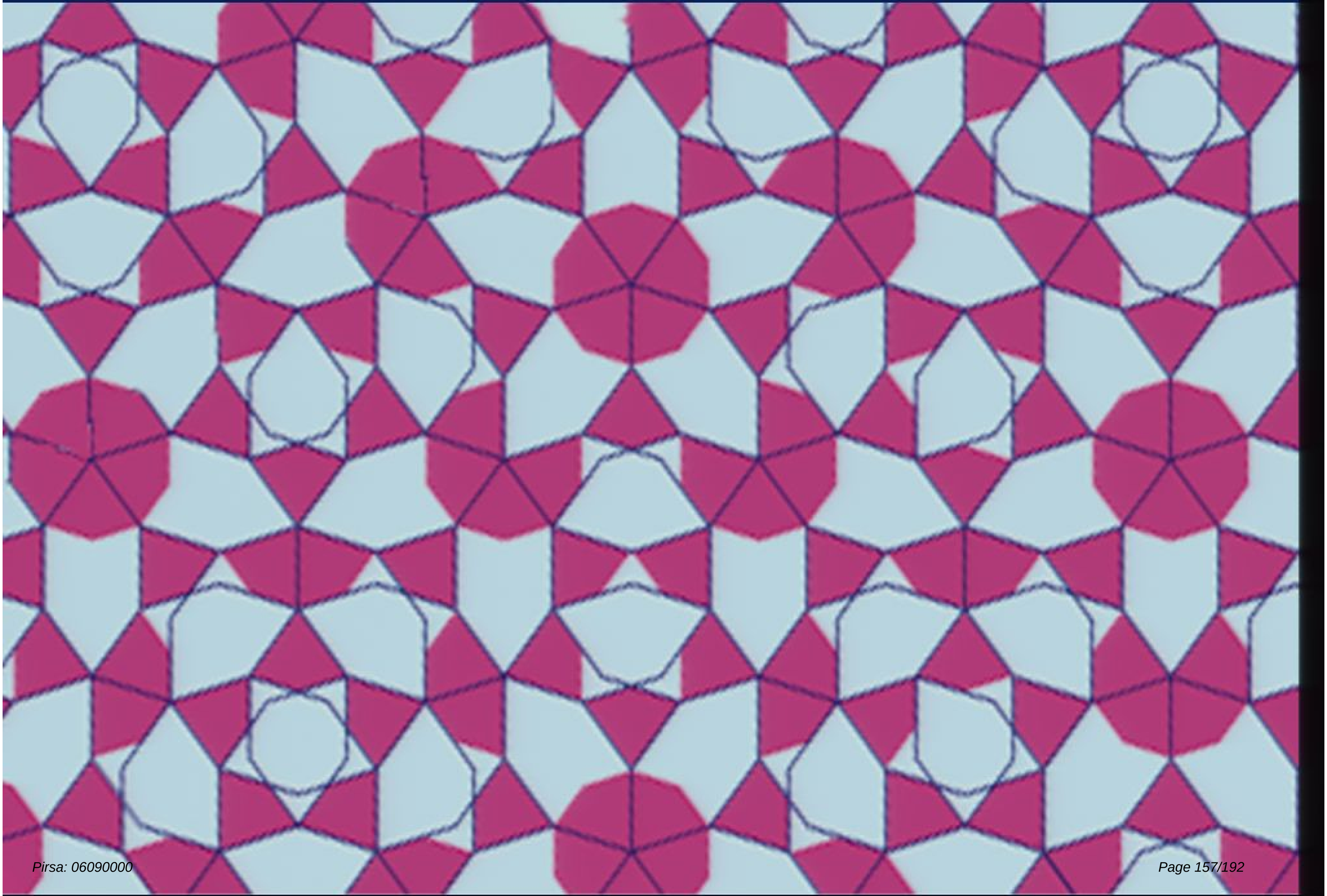




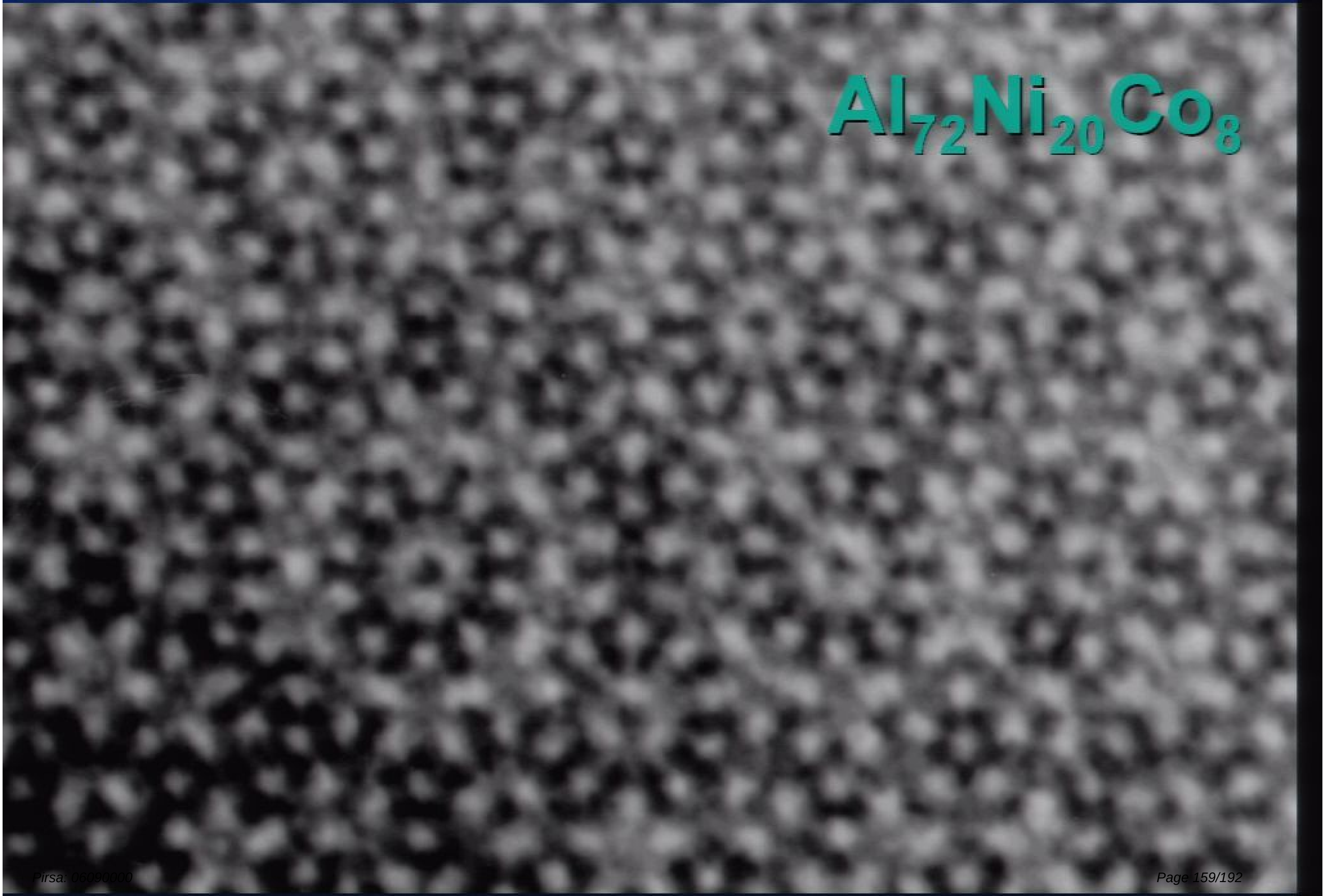


Overlap Rules → Maximizing Cluster Density

Clusters energetically favored →
Quasicrystal has minimum energy

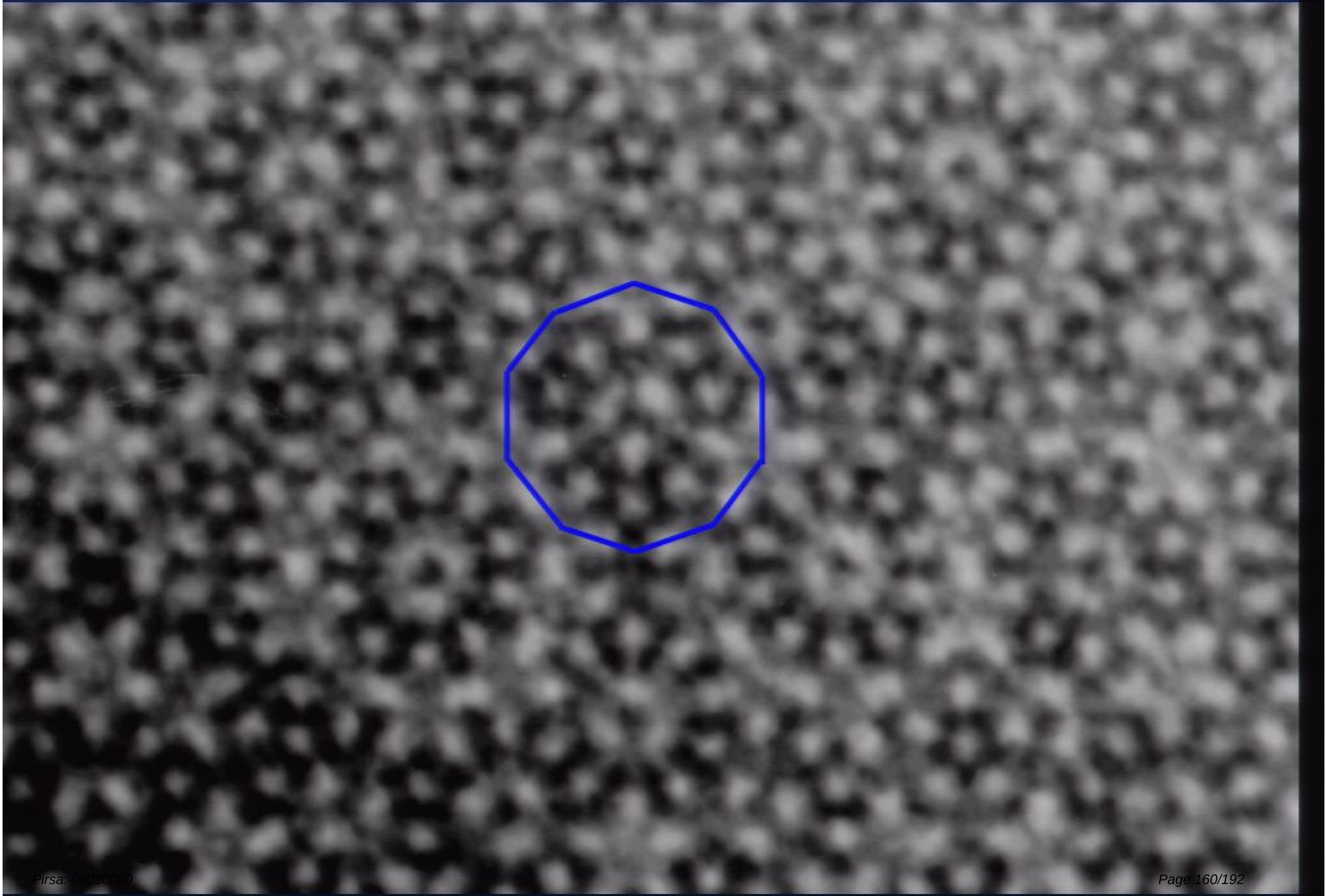
P.J. Steinhardt, H.-C. Jeong (1998)

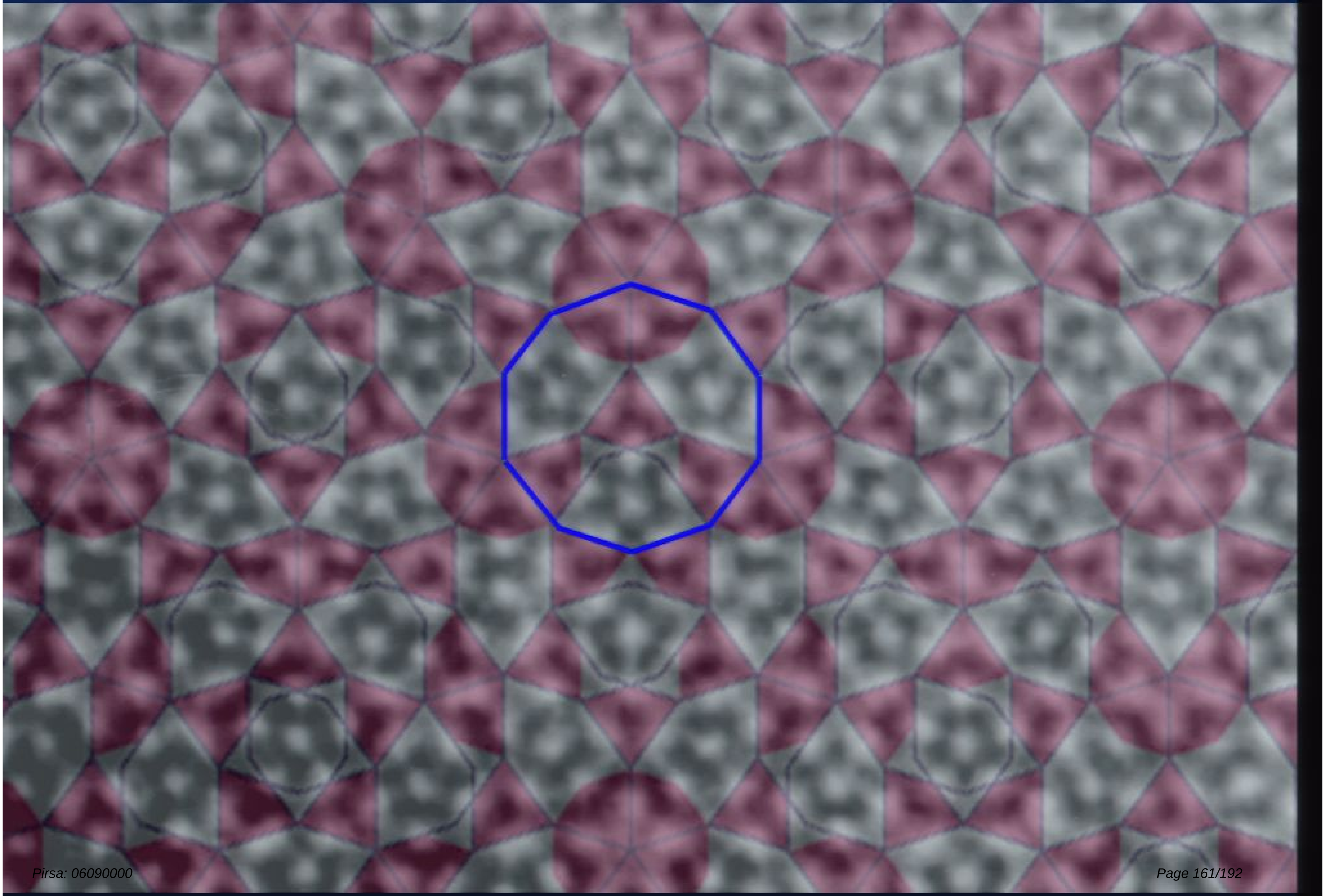
igh Angle Annular Dark Field

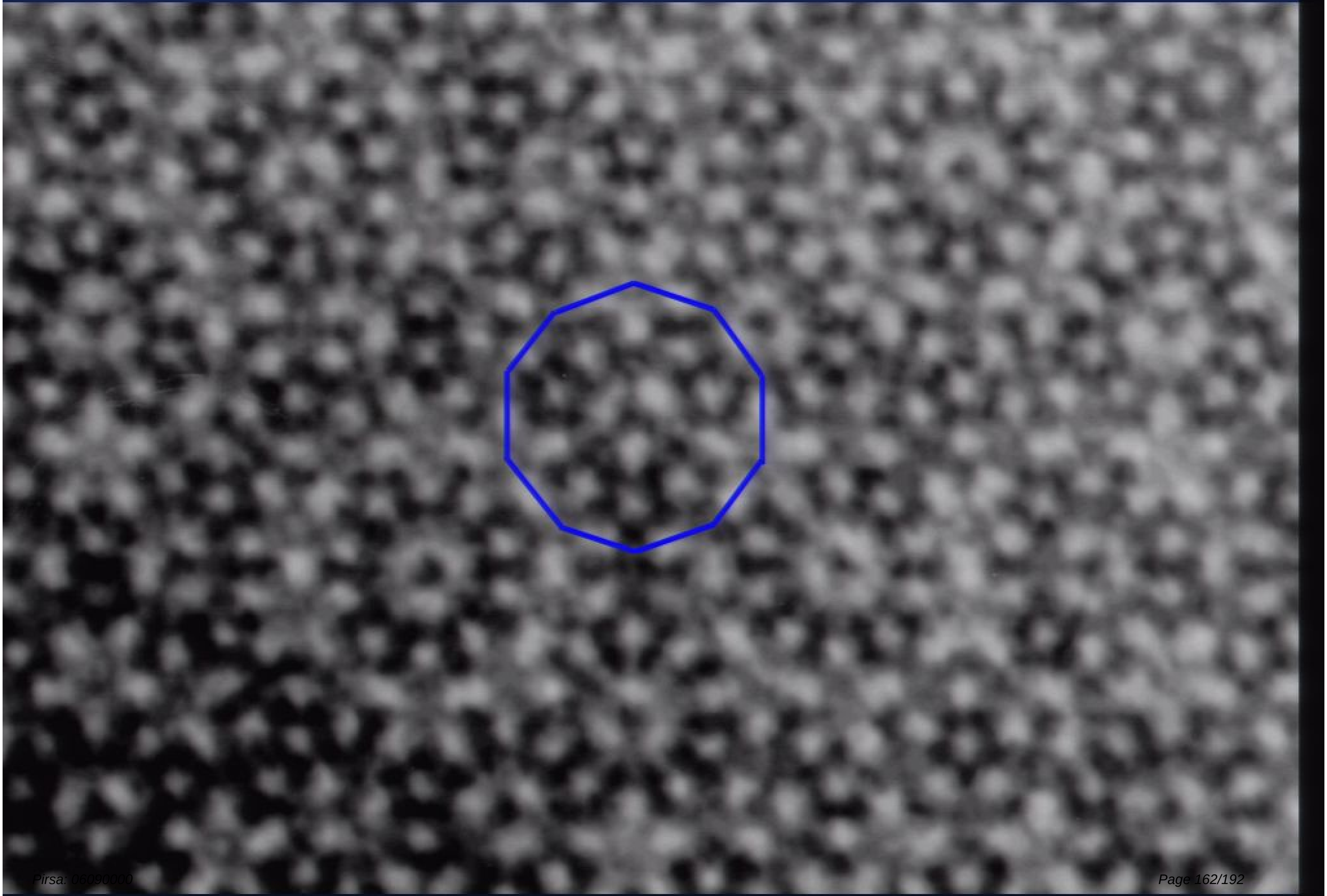


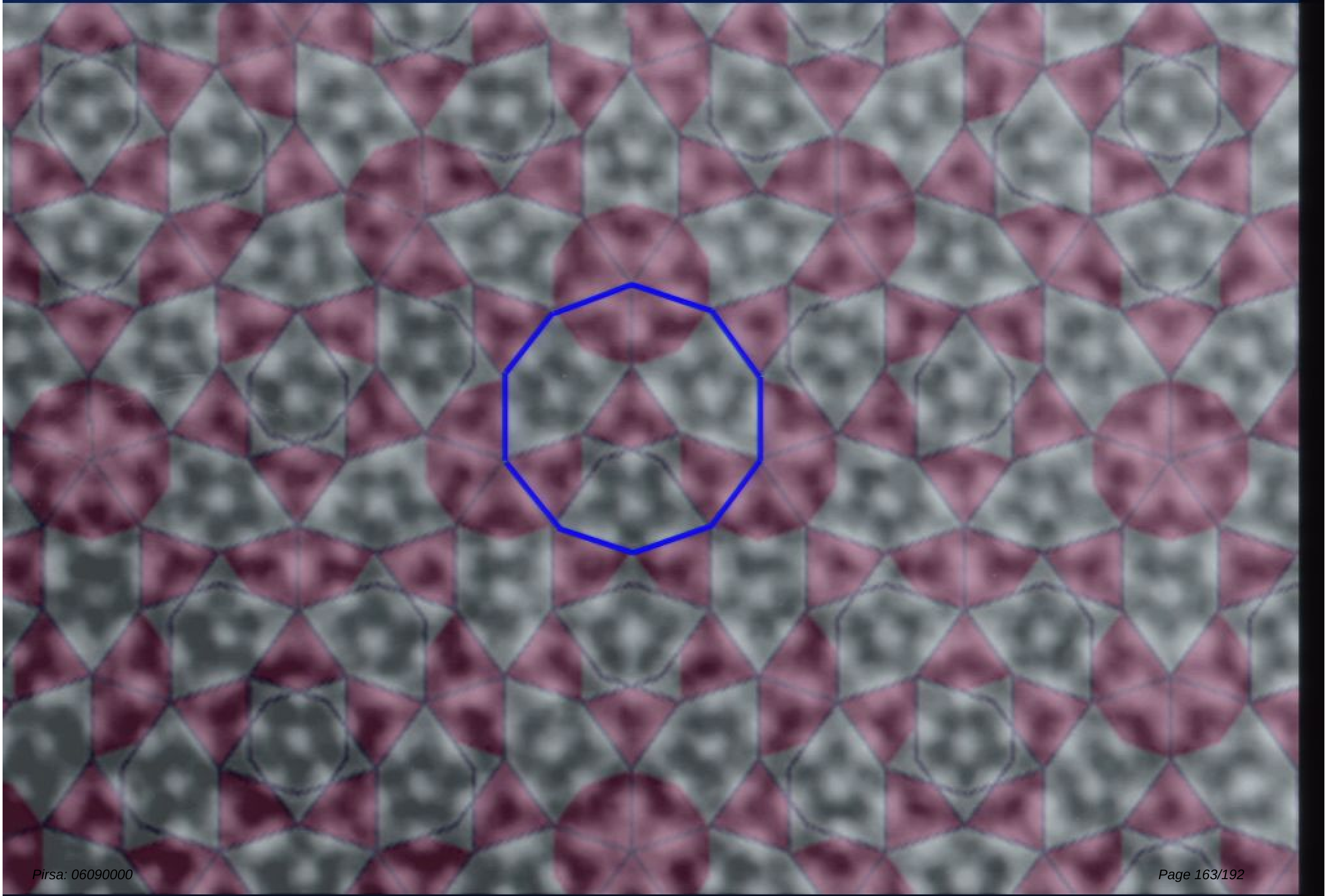
$Al_{72}Ni_{20}Co_8$

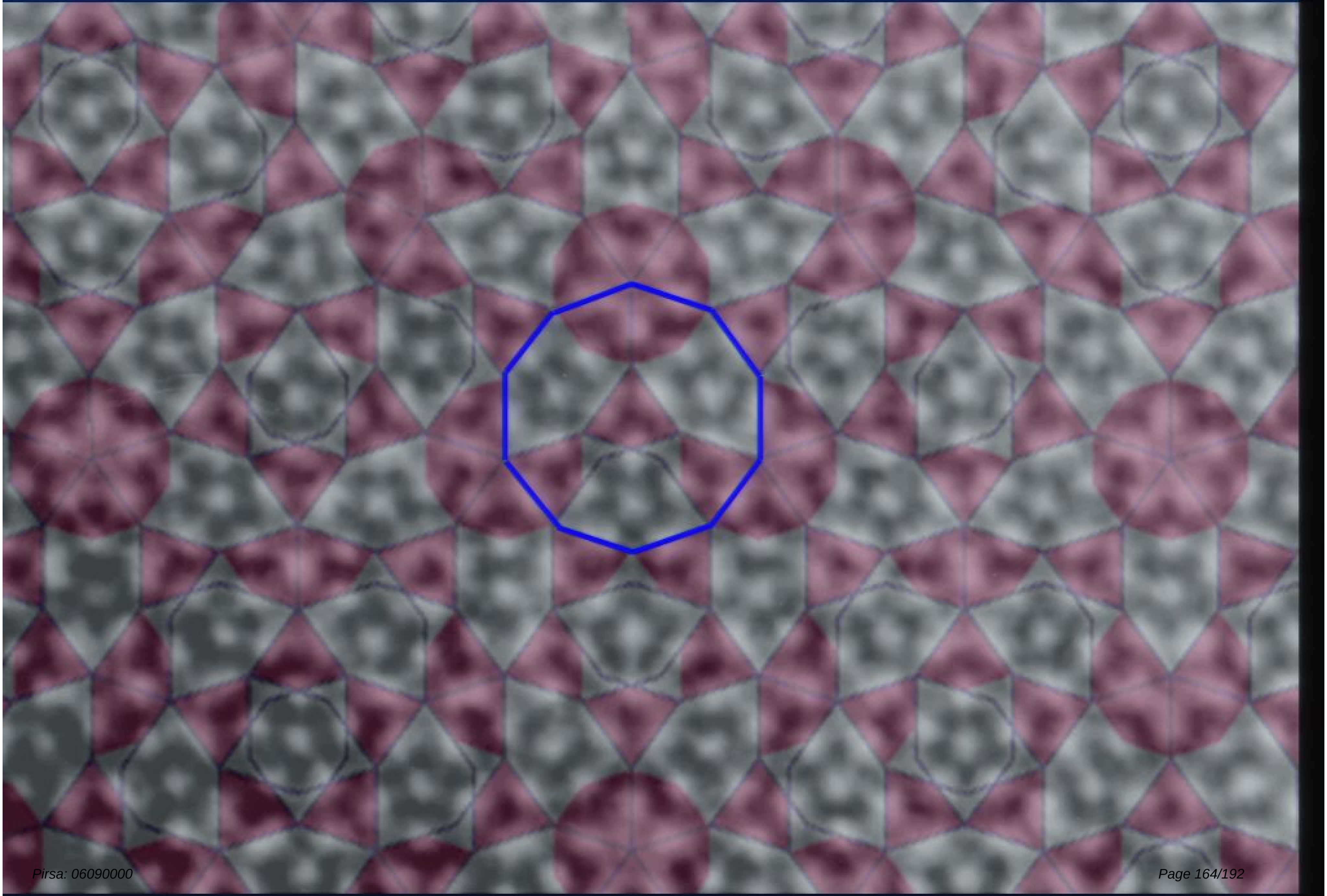
P.J. Steinhardt, H.-C. Jeong, K. Saitoh, M. Tanaka, E. Abe, A.P. Tsai

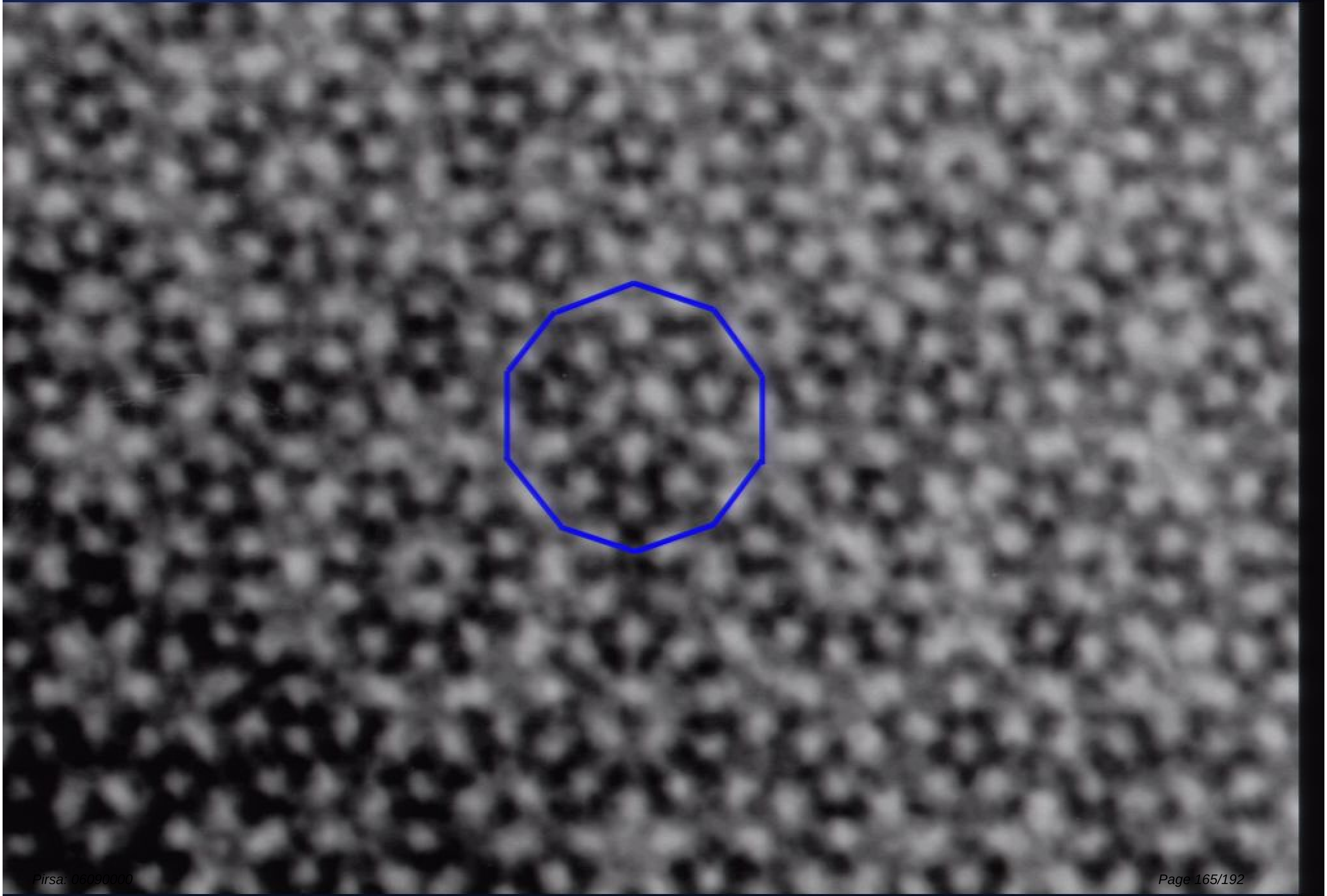


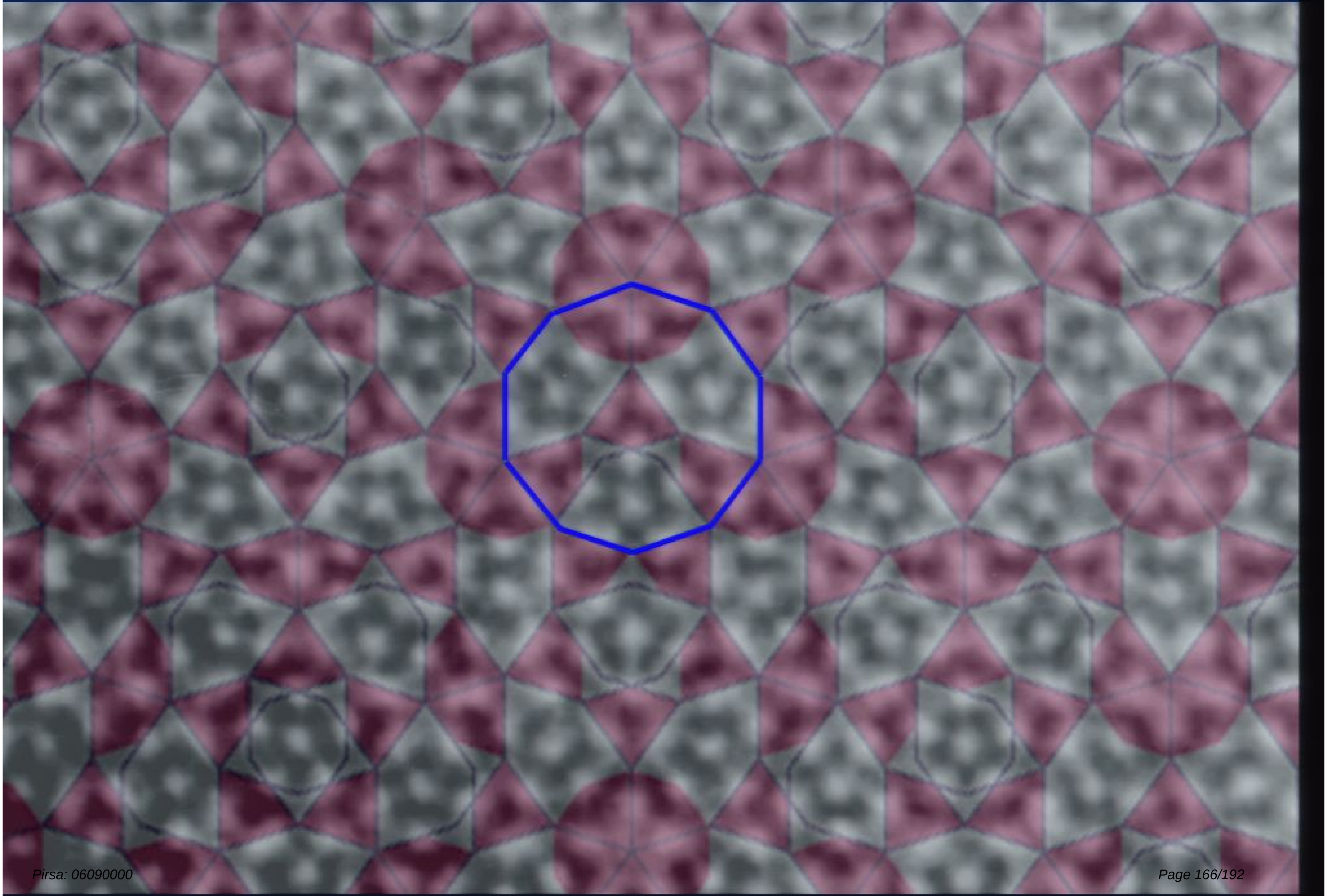


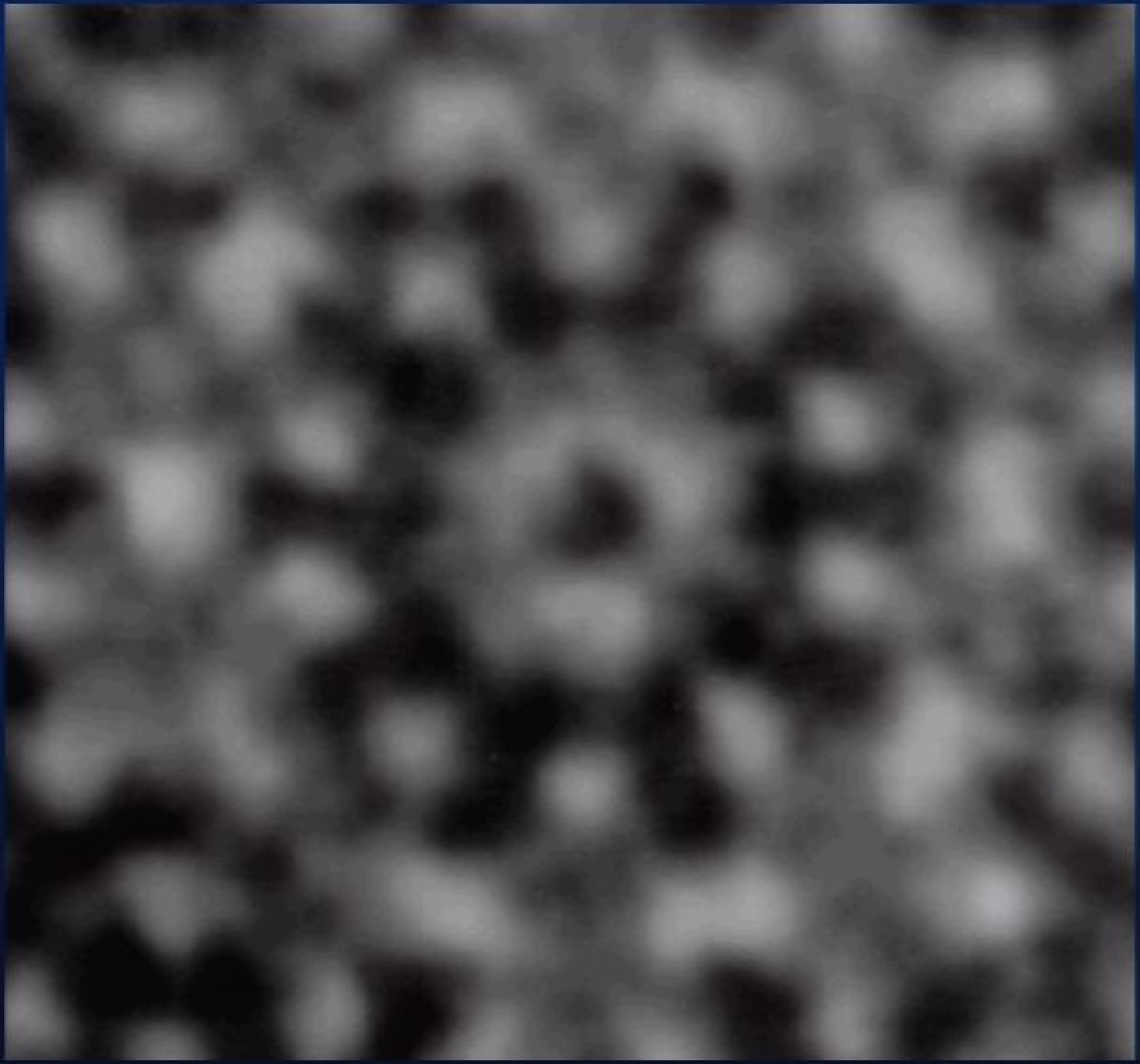


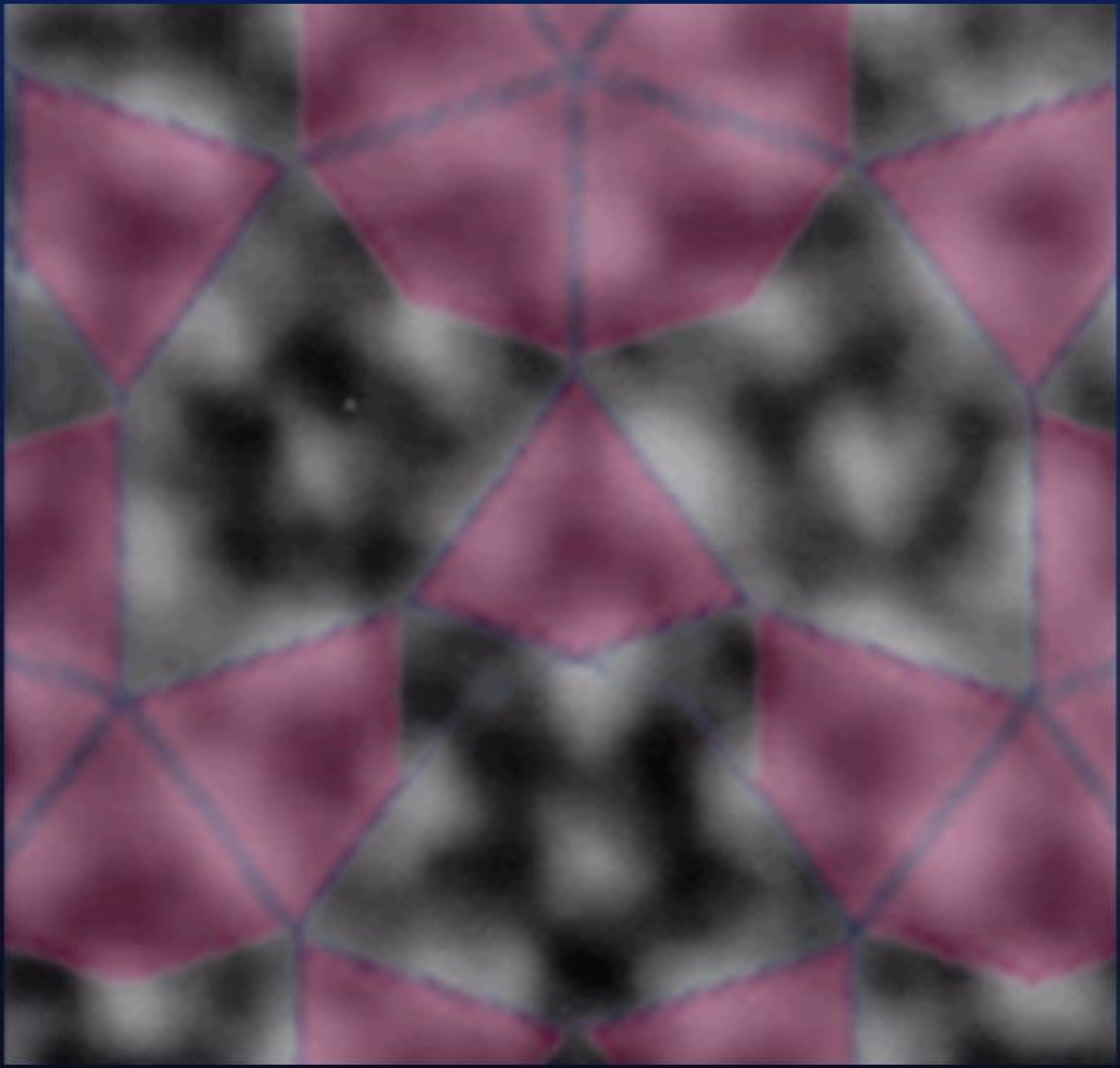












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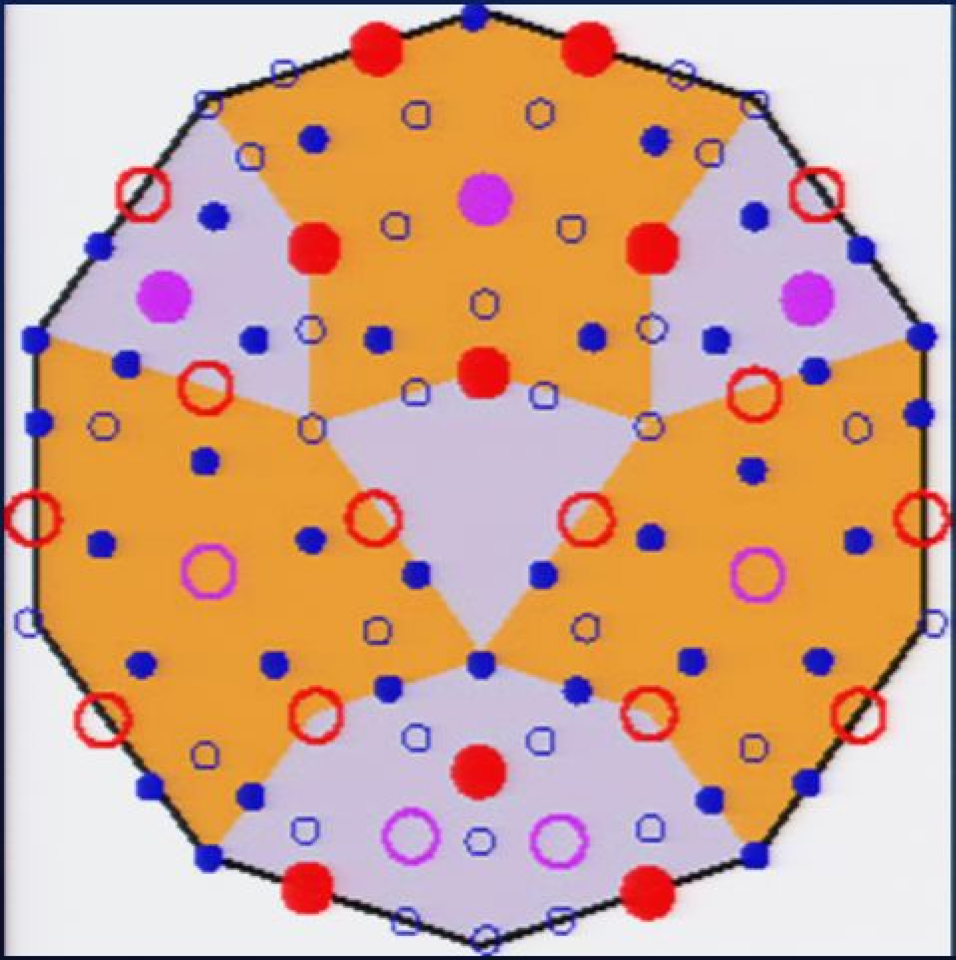

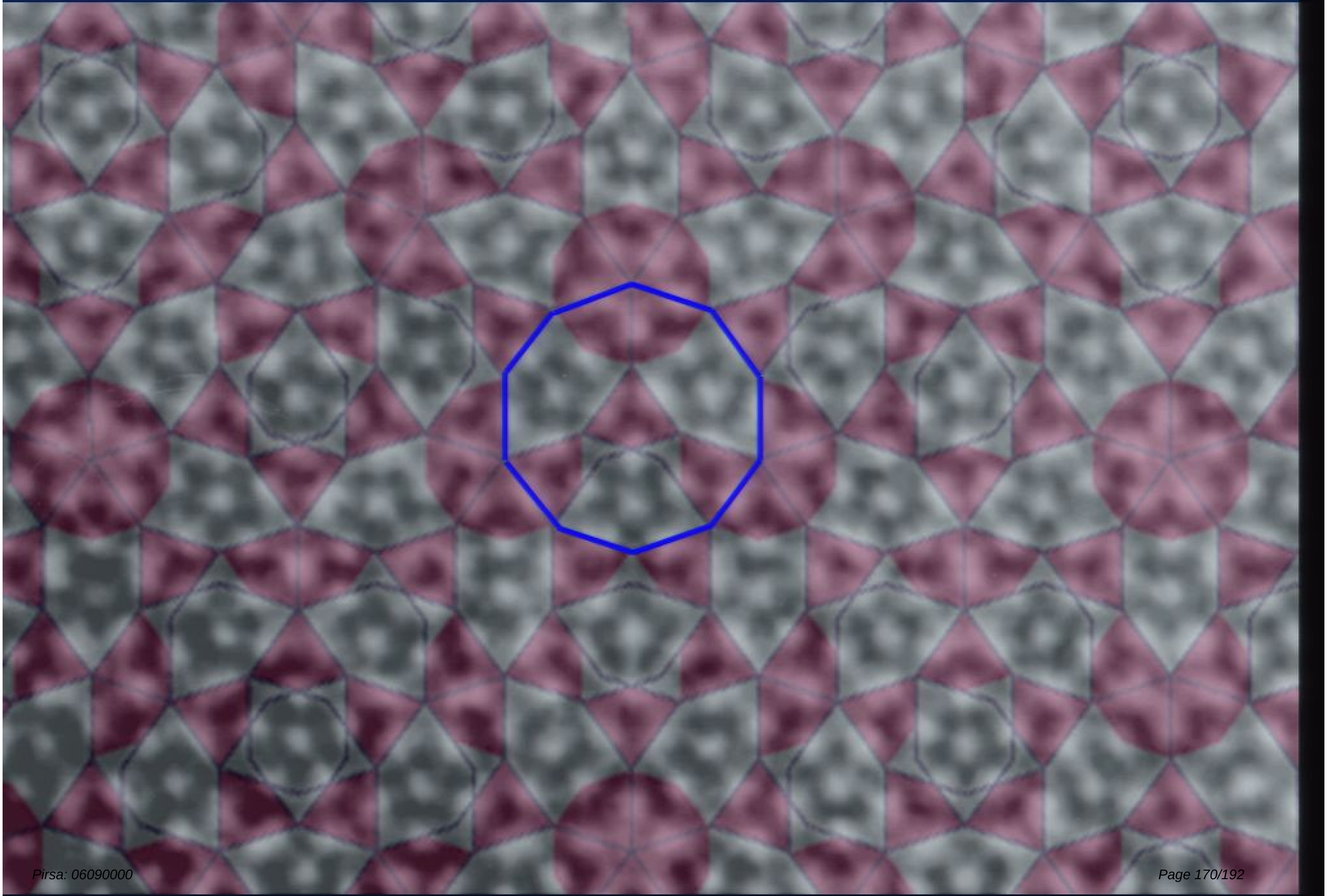

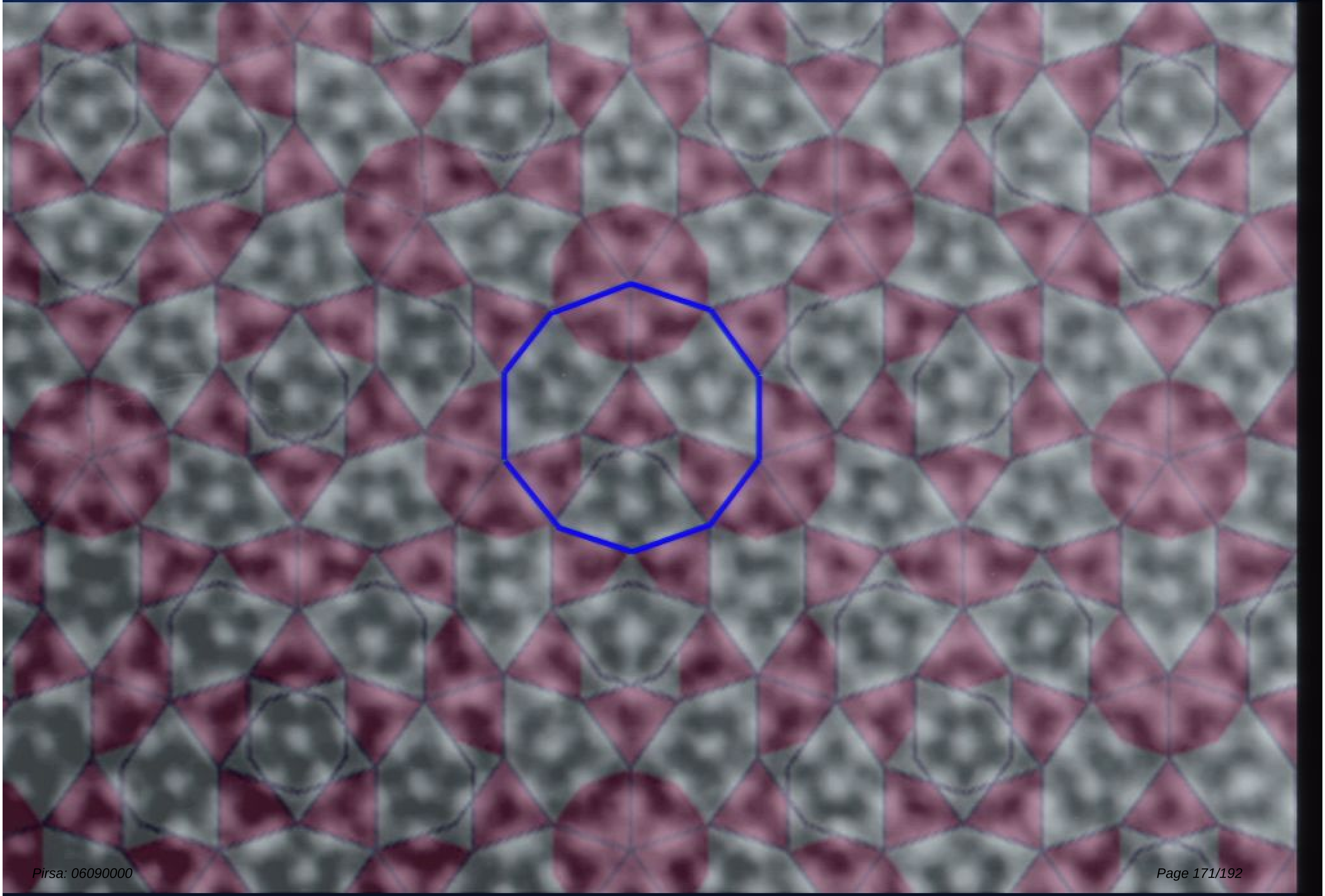

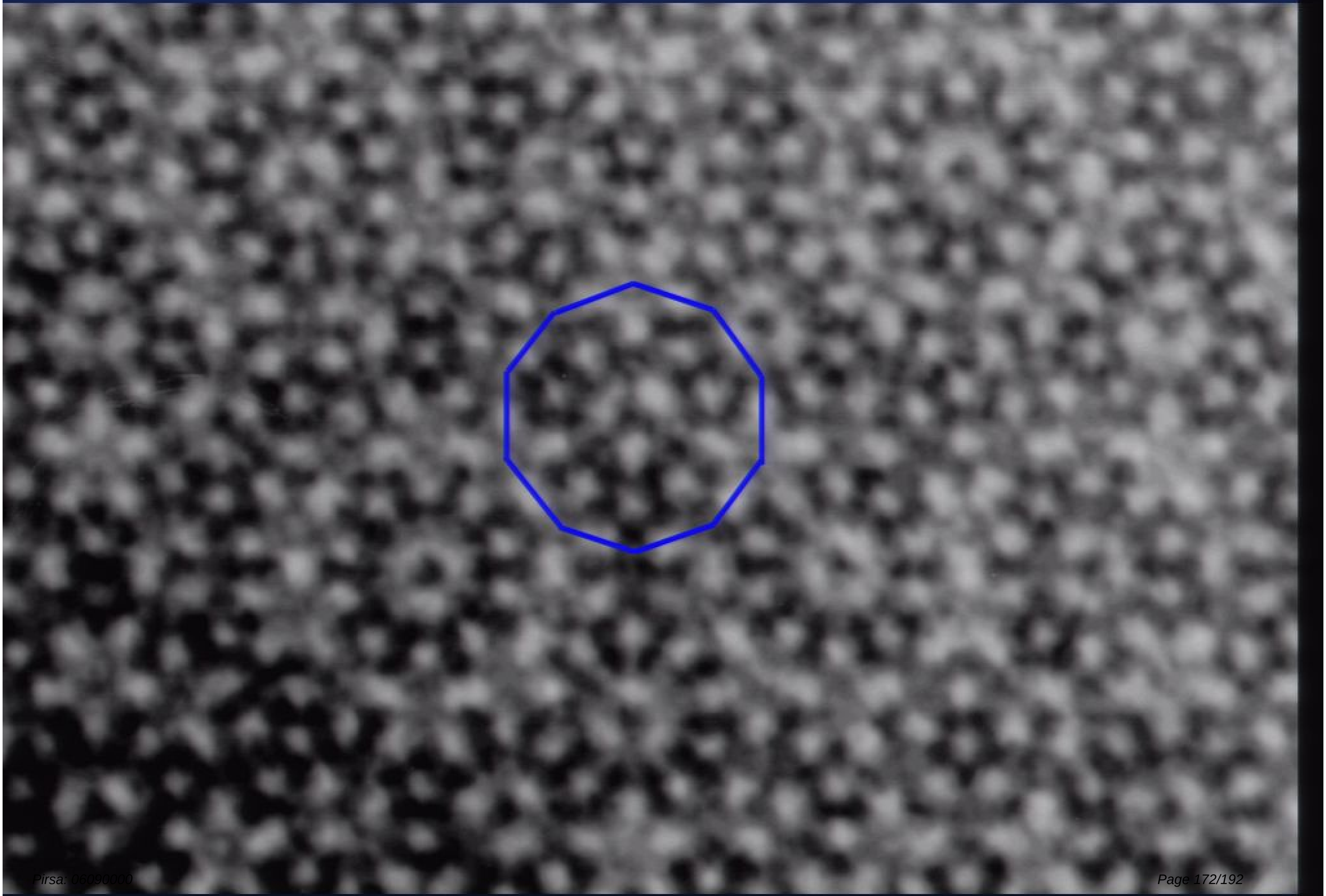

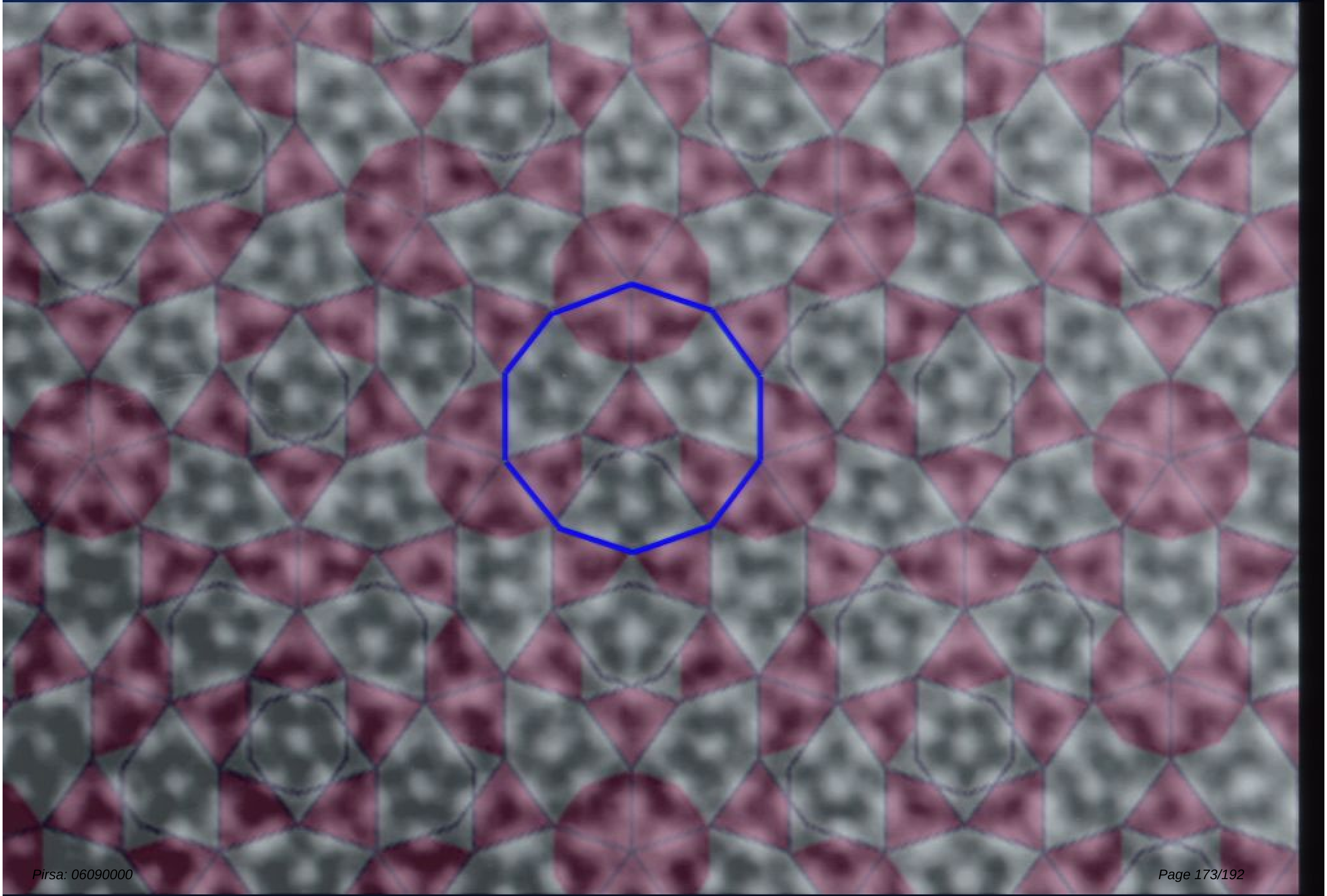

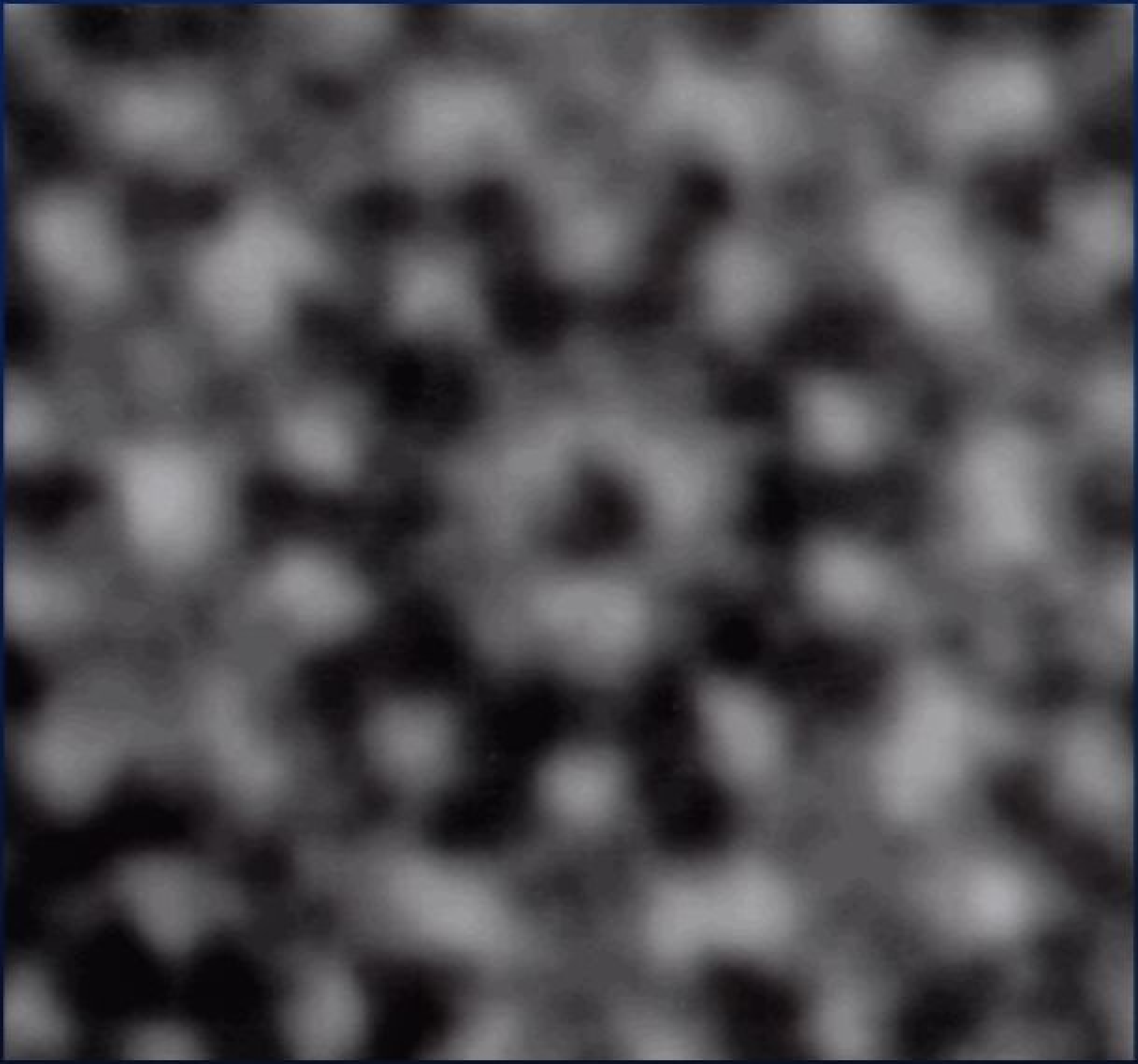

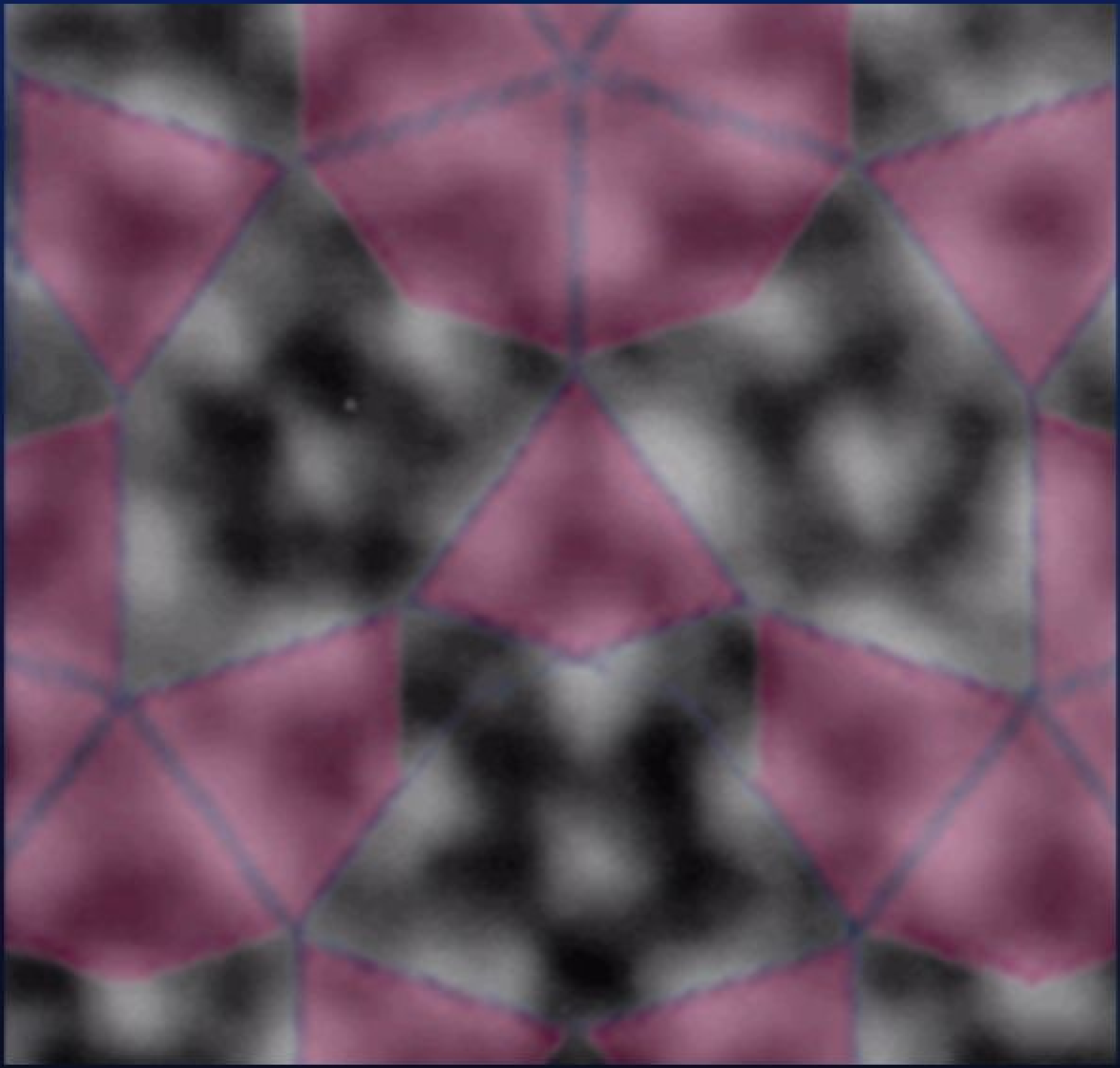

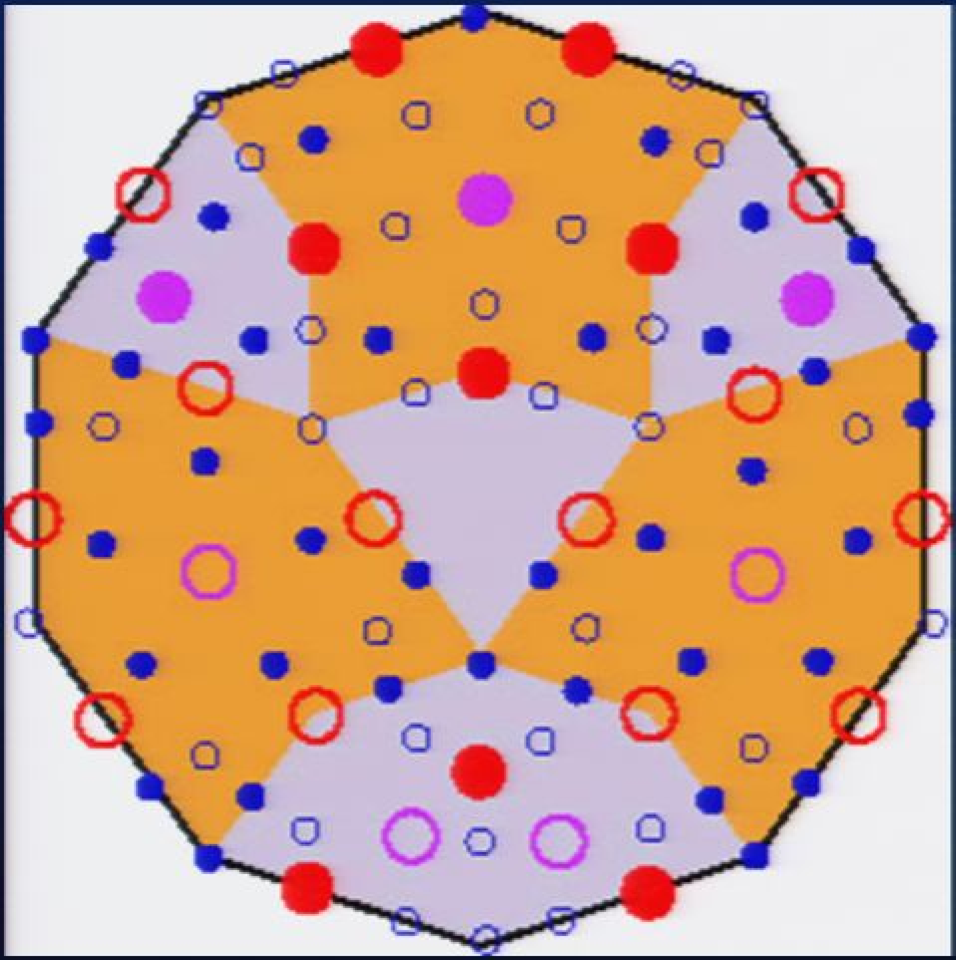

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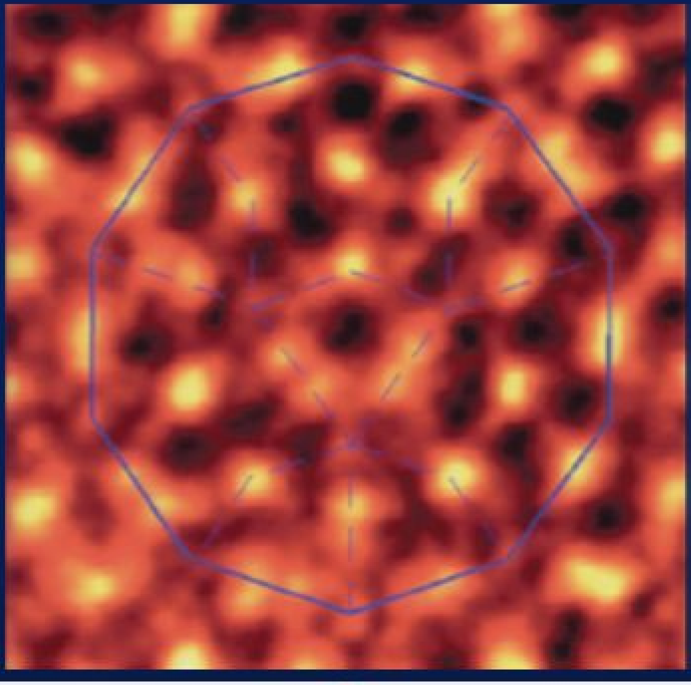
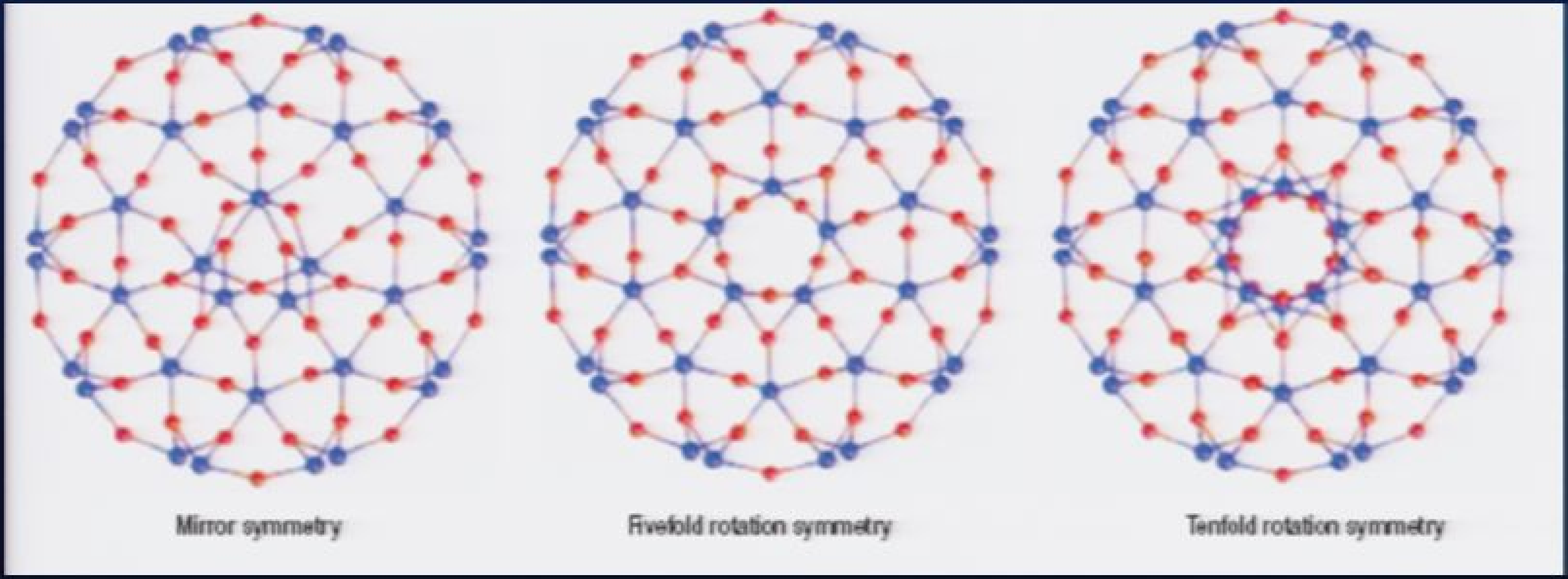




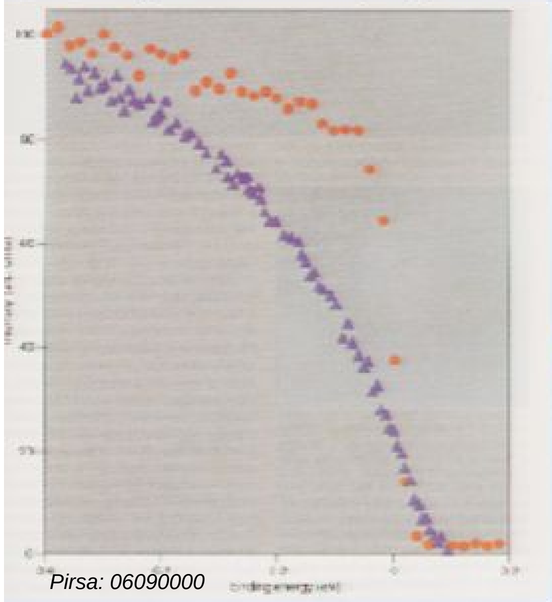
Prediction agrees with Later Higher Resolution Imaging

Yan & Pennycook (2001

New Physical Properties

- Diffraction
- Faceting

- Elastic Properties



- Electronic Properties

Cybernox

Collection

Cybernox Collection

N.B. The speaker has NO fiducial interest whatsoever in Cybernox.

Epilogue