



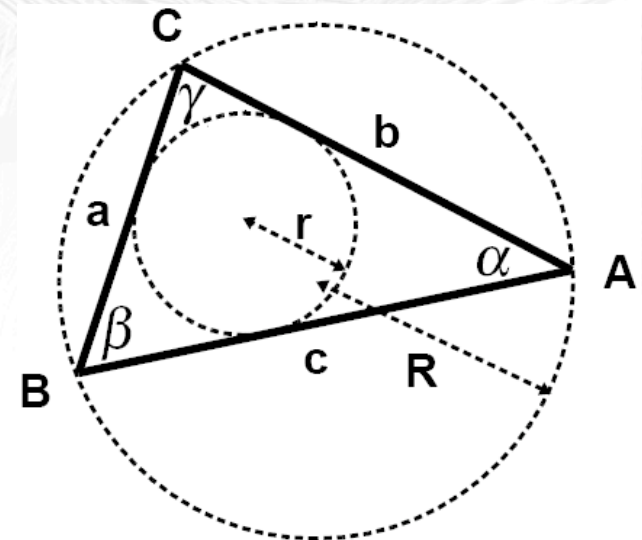
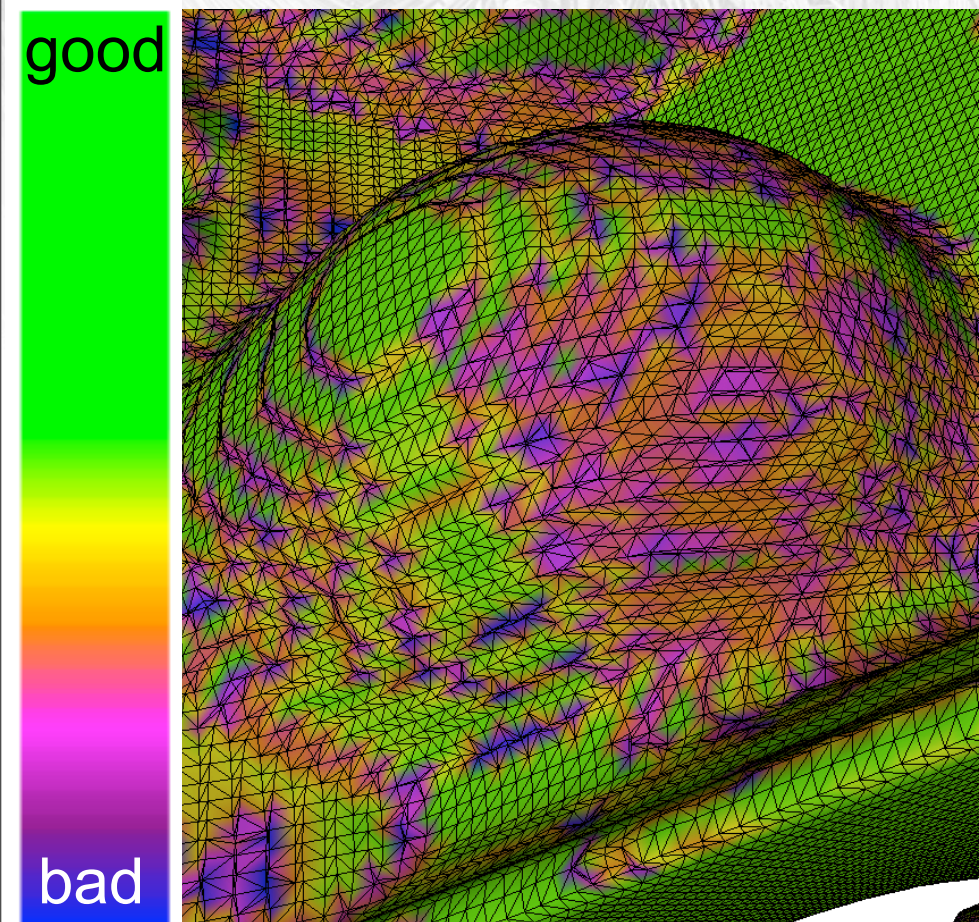
VisWeek 08
VIS • INFOVIS • VAST

Edge Groups: An Approach to Understanding the Mesh Quality of Marching Methods

Carlos A. Dietrich, Carlos Scheidegger

João L. D. Comba, Luciana Porcher Nedel, Cláudio T. Silva

Triangle Quality of Marching Cubes

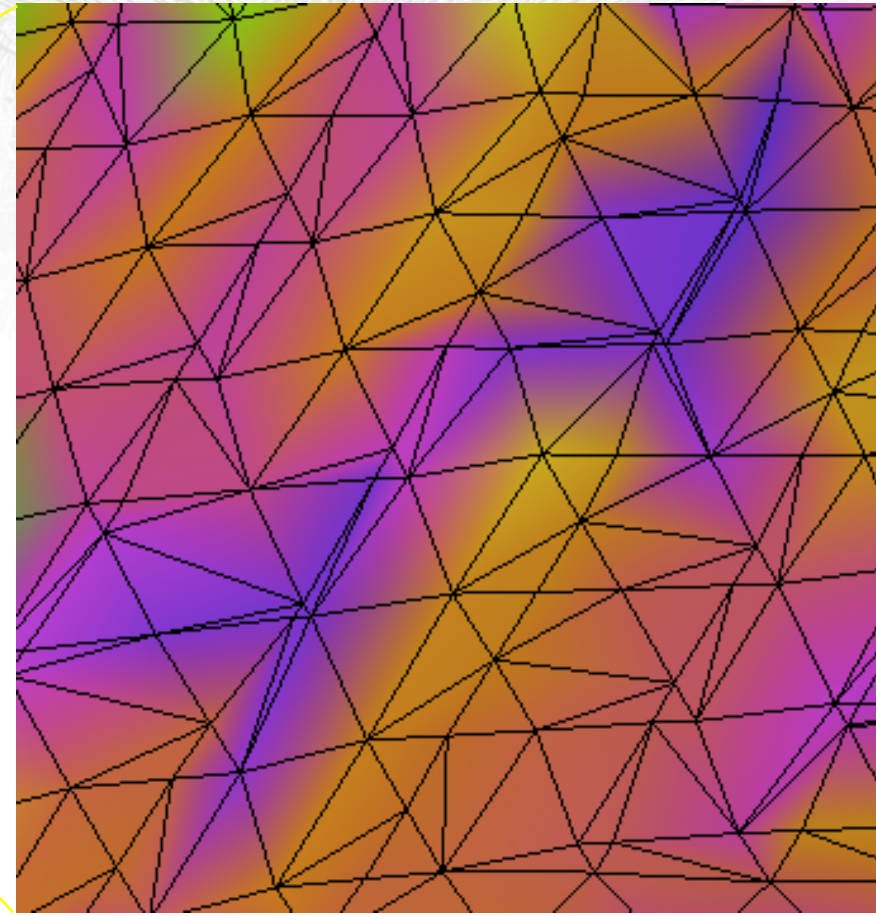
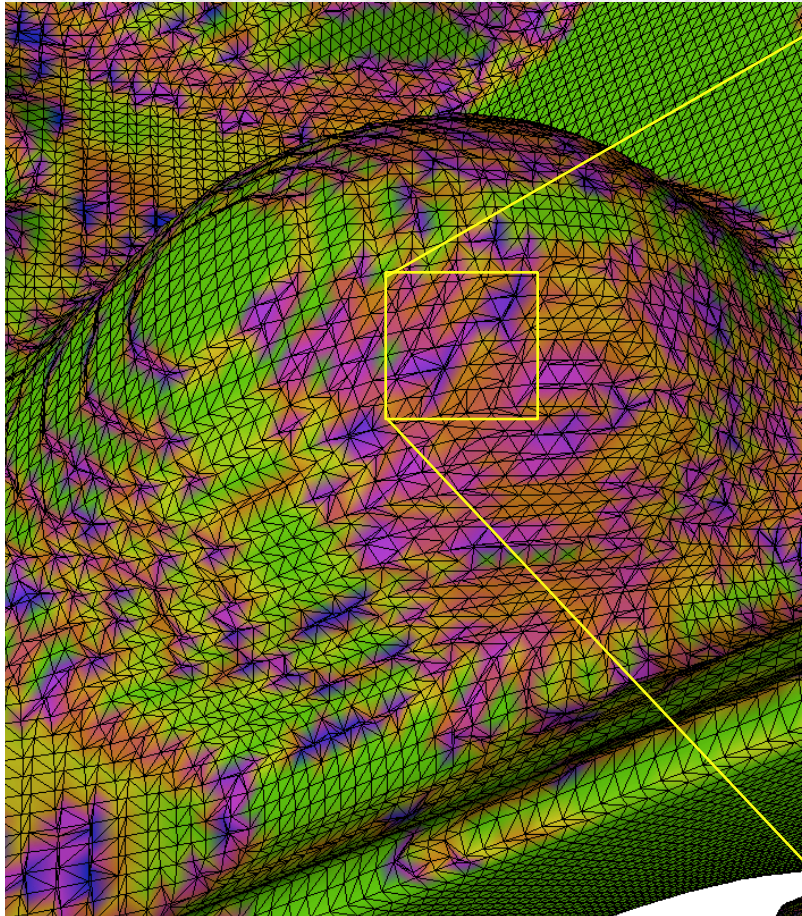


Radii ratio ($2r/R$)

Triangle Quality of Marching Cubes

- Mostly good quality triangles. But some very poor quality triangles

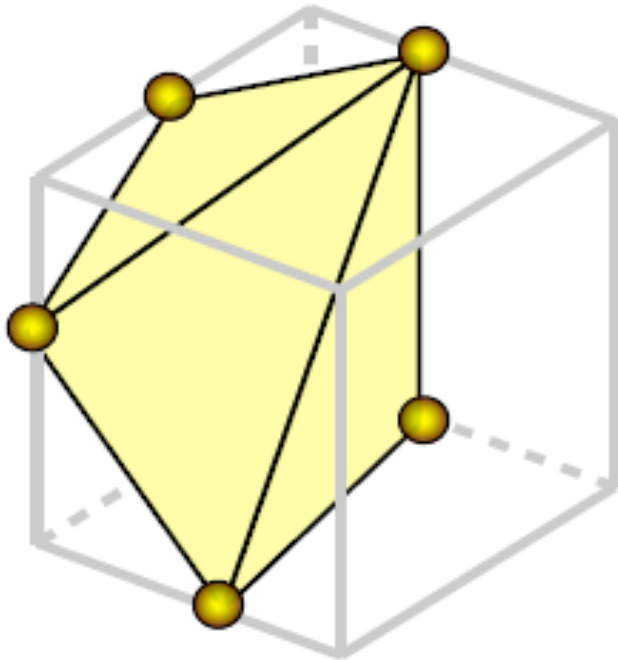
good



bad

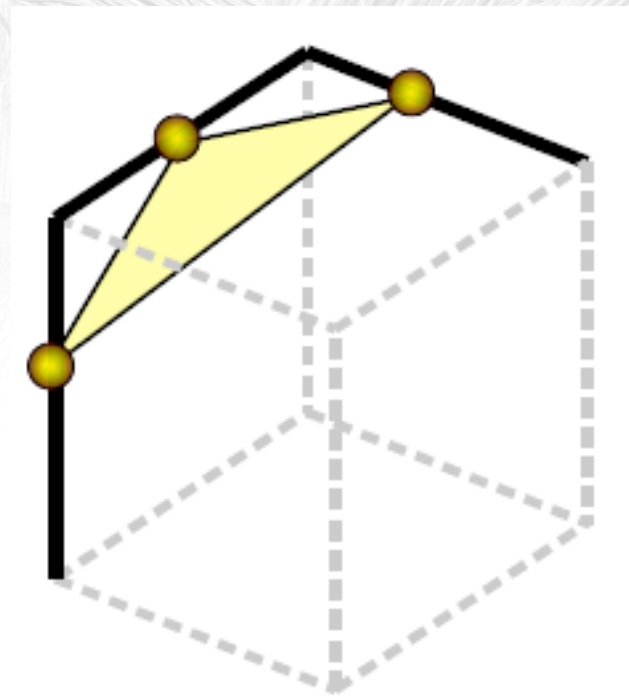
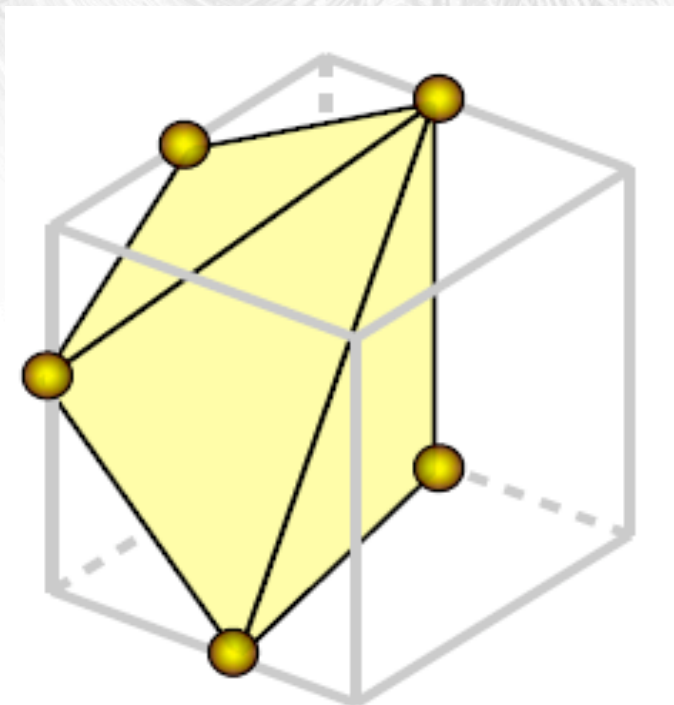
Triangle Quality of Marching Cubes

- In this work we propose a way to understand why this happens.



Triangle Quality of Marching Cubes

- Look at each triangle individually

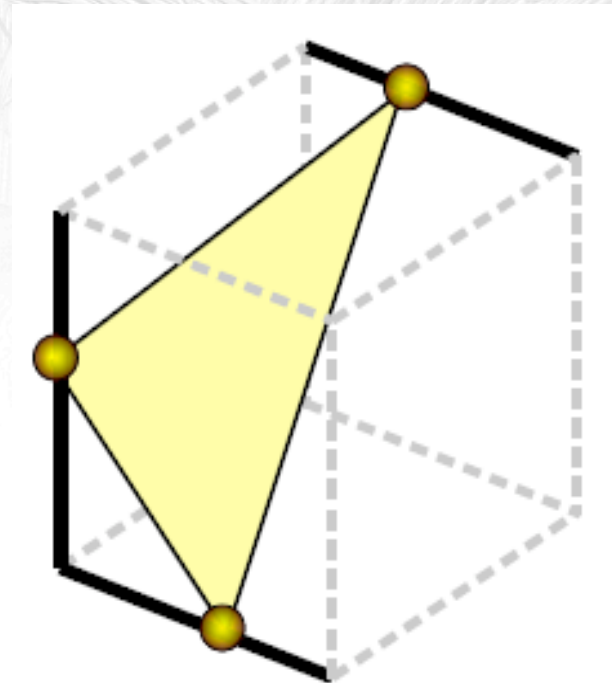
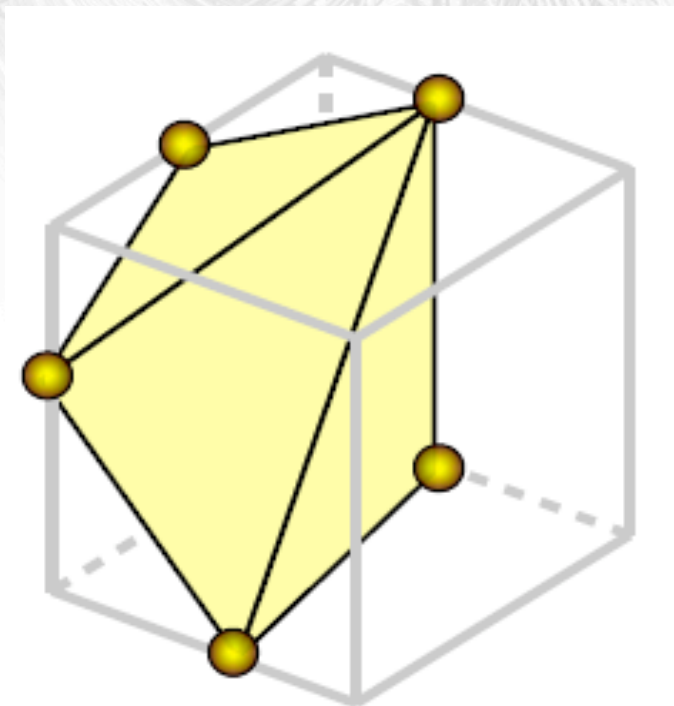


Important Observation:

Each triangle generated by MC has vertices only over active edges. Therefore, it **does not** generate arbitrary triangles

Triangle Quality of Marching Cubes

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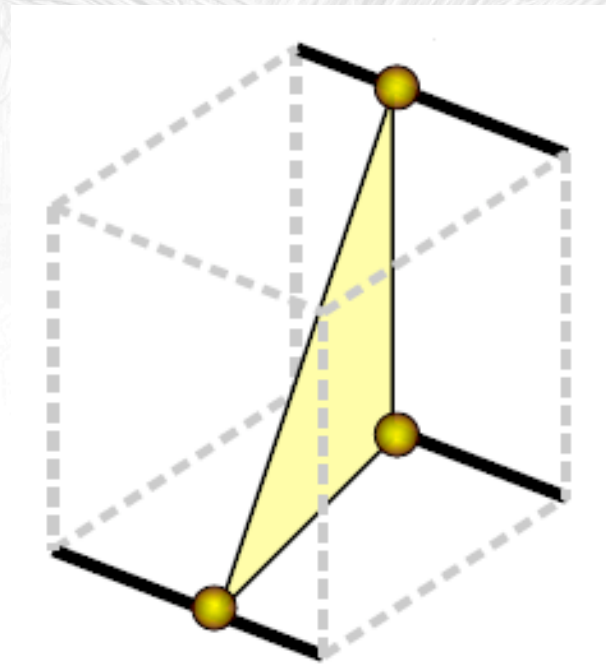
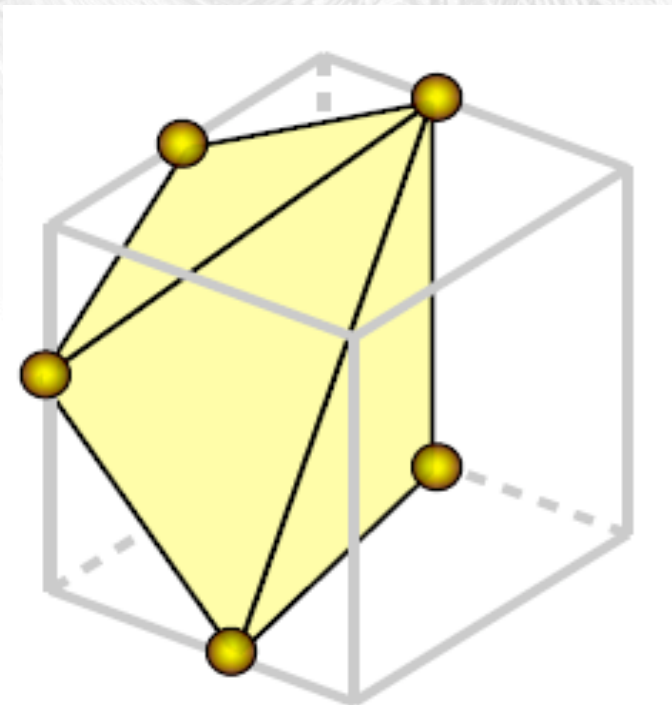


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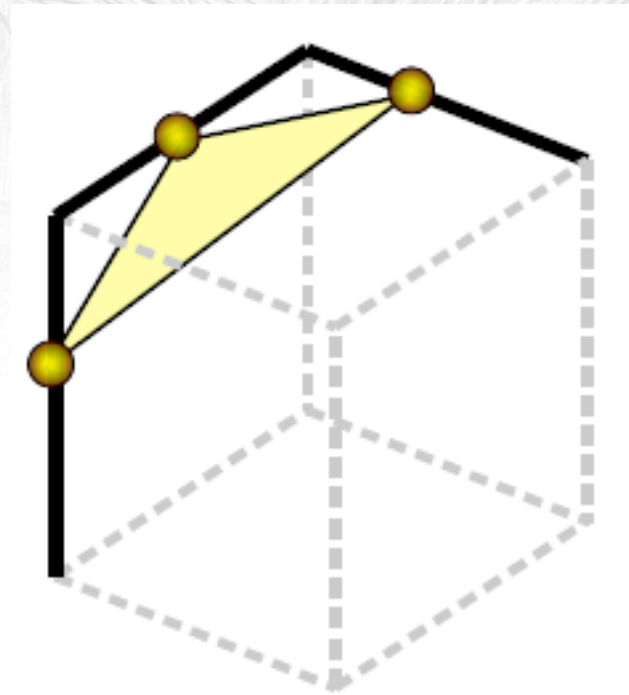
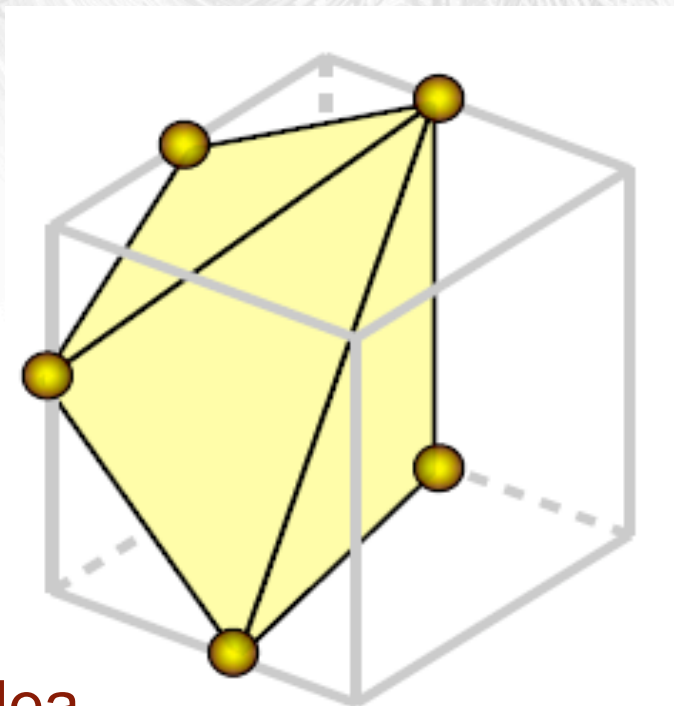


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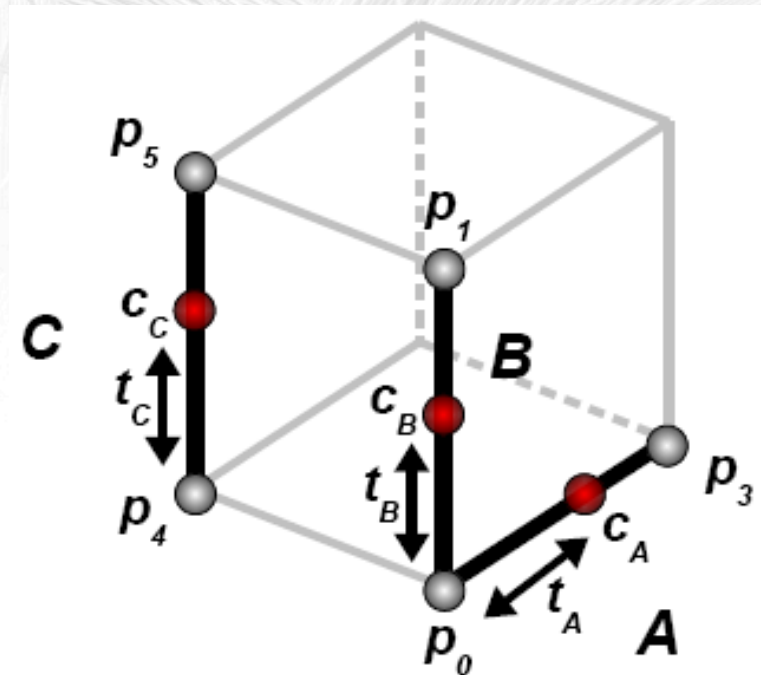
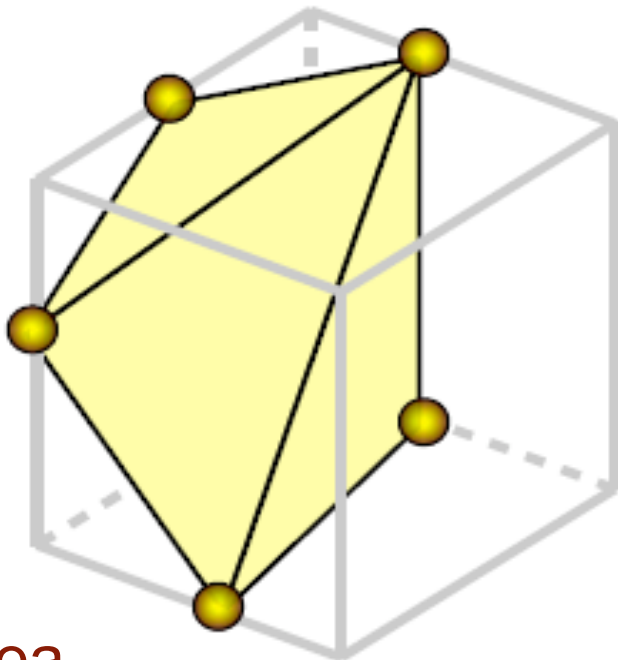


Idea

Since three **active edges** define a triangle, we could evaluate all possible triangles generated by such **configuration**

Triangle Quality of Marching Cubes

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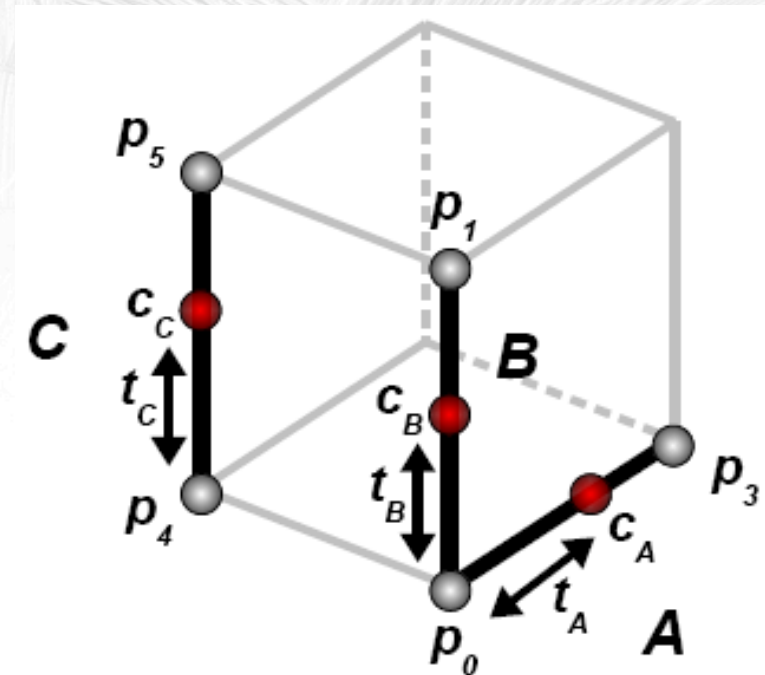
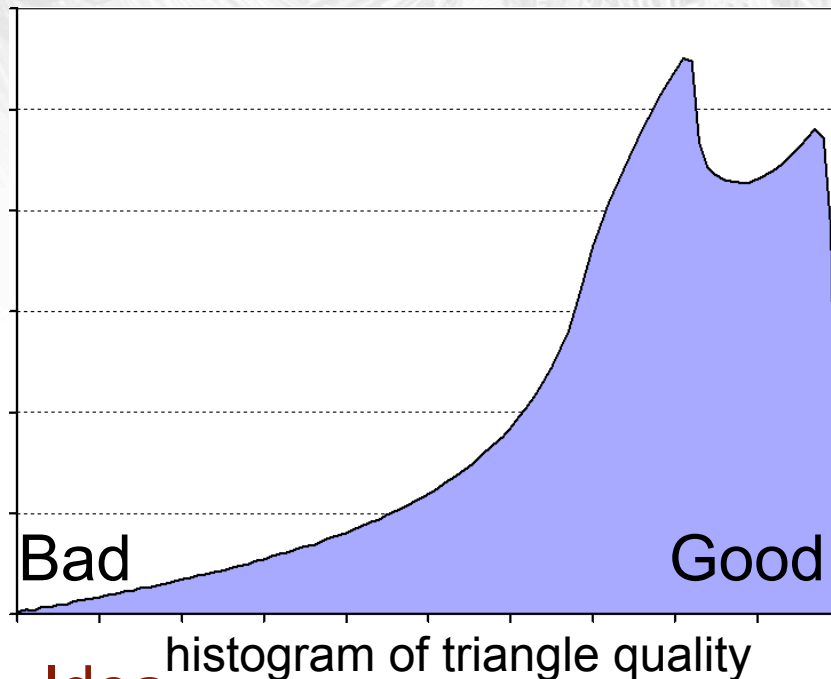


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Triangle Quality of Marching Cubes

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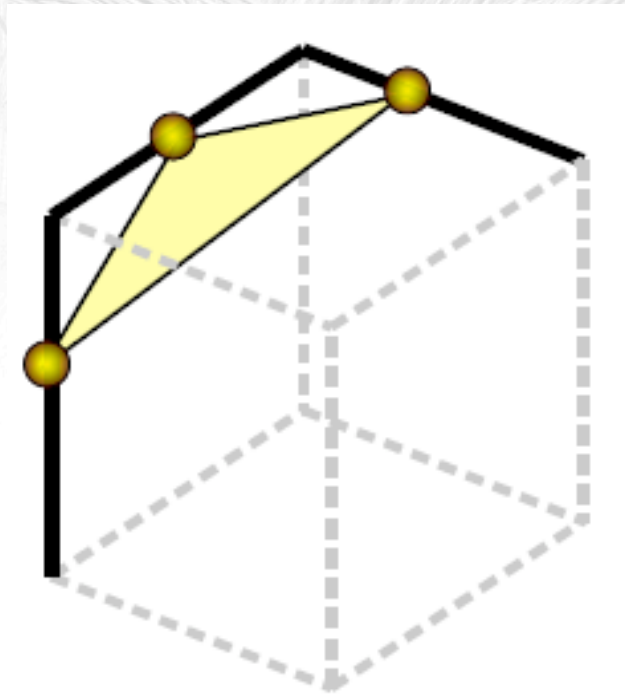
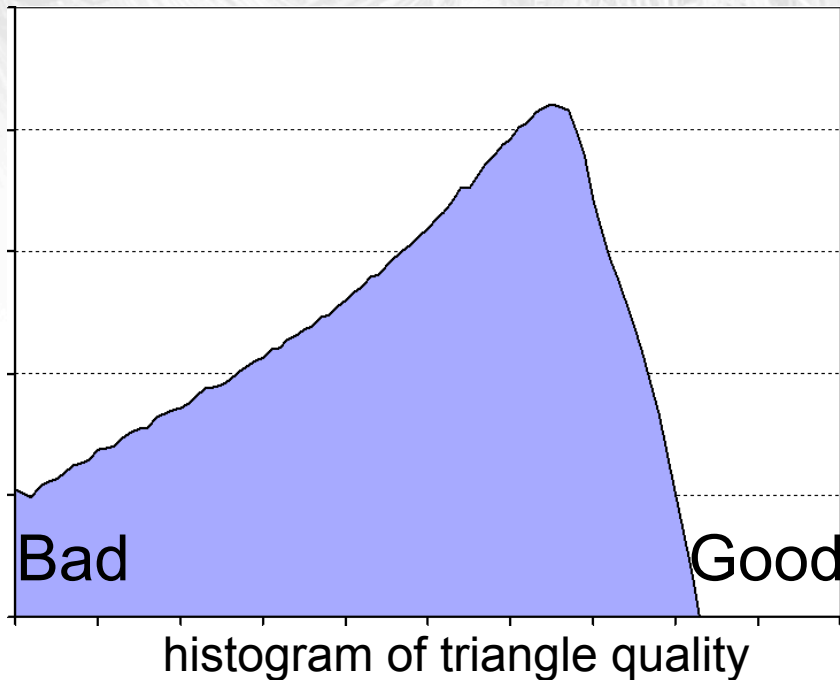


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Triangle Quality of Marching Cubes

- Several conclusions can be derived



Interesting Observation

This configuration is responsible for the worst triangles of MC !!!

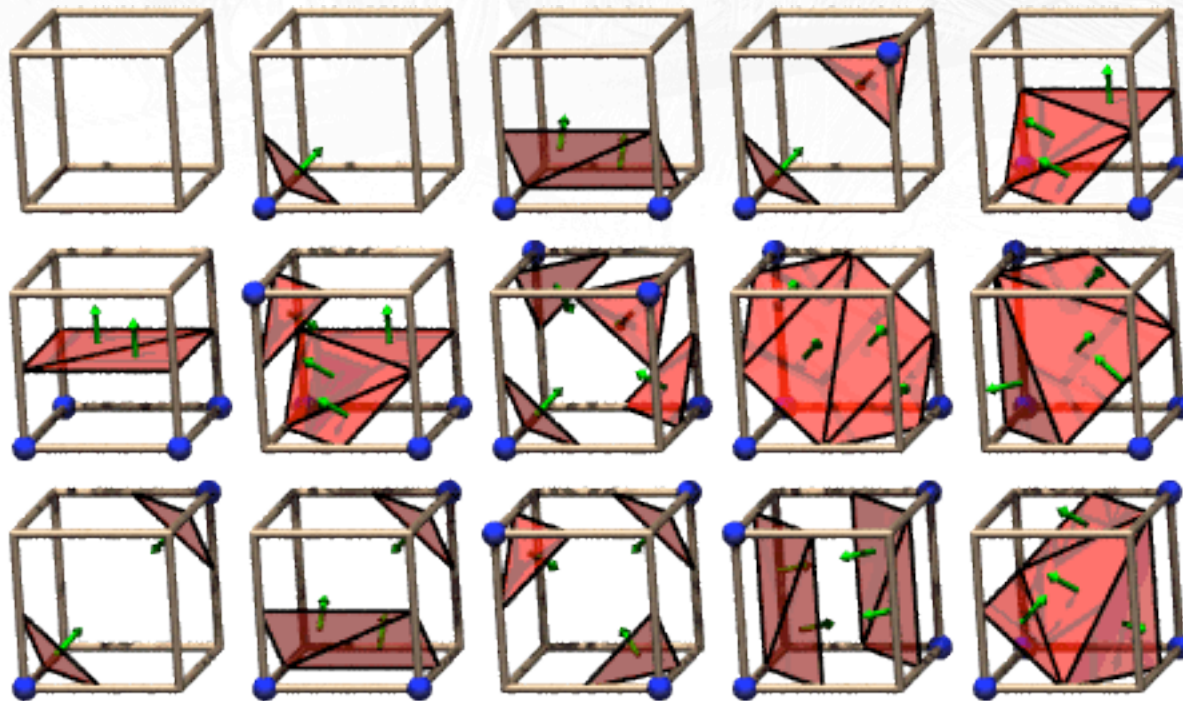
Triangle Quality of Marching Cubes



- Other Questions to answer:
 - How many cases of edge configurations ?

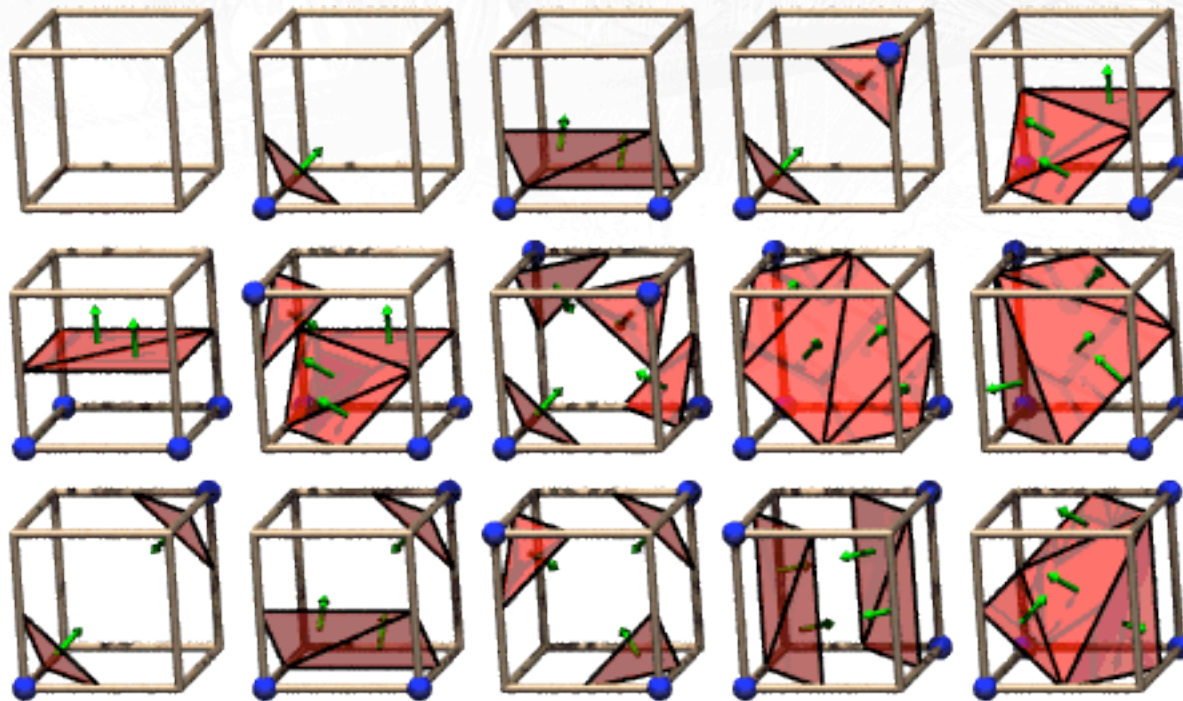
Triangle Quality of Marching Cubes

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Triangle Quality of Marching Cubes

- Other Questions to answer:
 - How many cases of edge configurations ?
 - Is it similar to Marching Cubes Cases Enumeration ? **YES, but at edge level**



Outline



- Motivation
- **Edge Groups in Cubic Cells**
- Improving Triangle Quality Based on Edge Groups
- Results
- Conclusions

Edge Groups in Cubic Cells



- Counting Cases in MC
 - [Lorensen and Cline 87] 15 cases based on inspection
 - [Nielson et al 2002] 23 cases by rotation only
 - [Banks et al 2004] formal proof using group theory

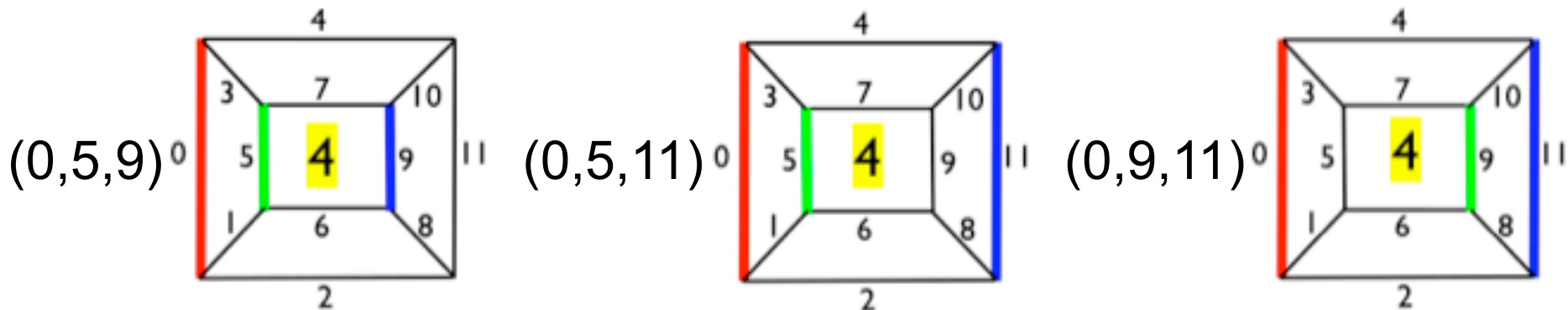
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 - Edge configuration (e_0, e_1, e_2) : 3 different edges of the cube
 - **Edge (Symmetry) Group**: collection of edge configurations that can be transformed into another by symmetry transformations (e.g. rotations and improper reflections)

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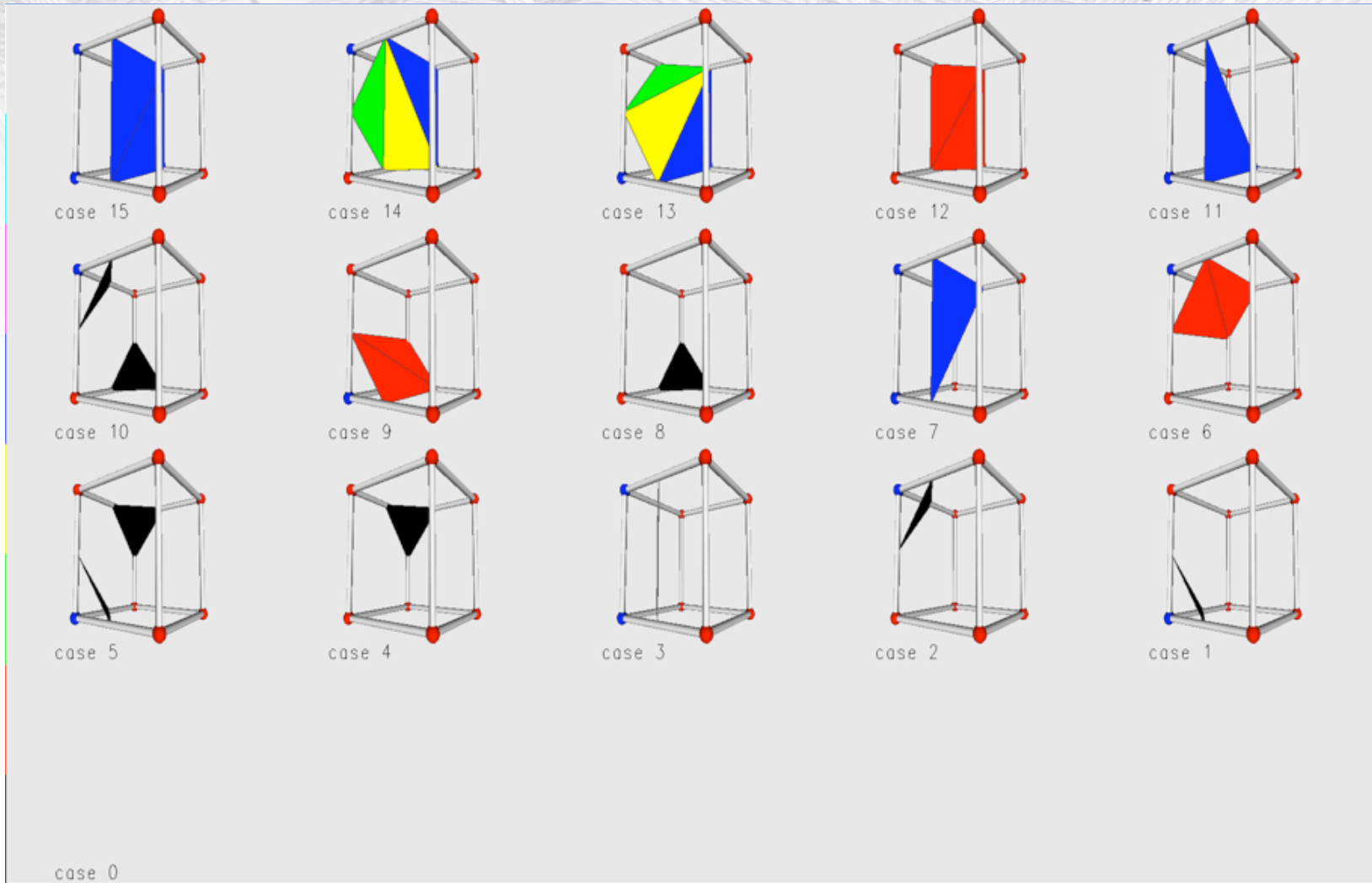


Counting Cases in Edge Groups

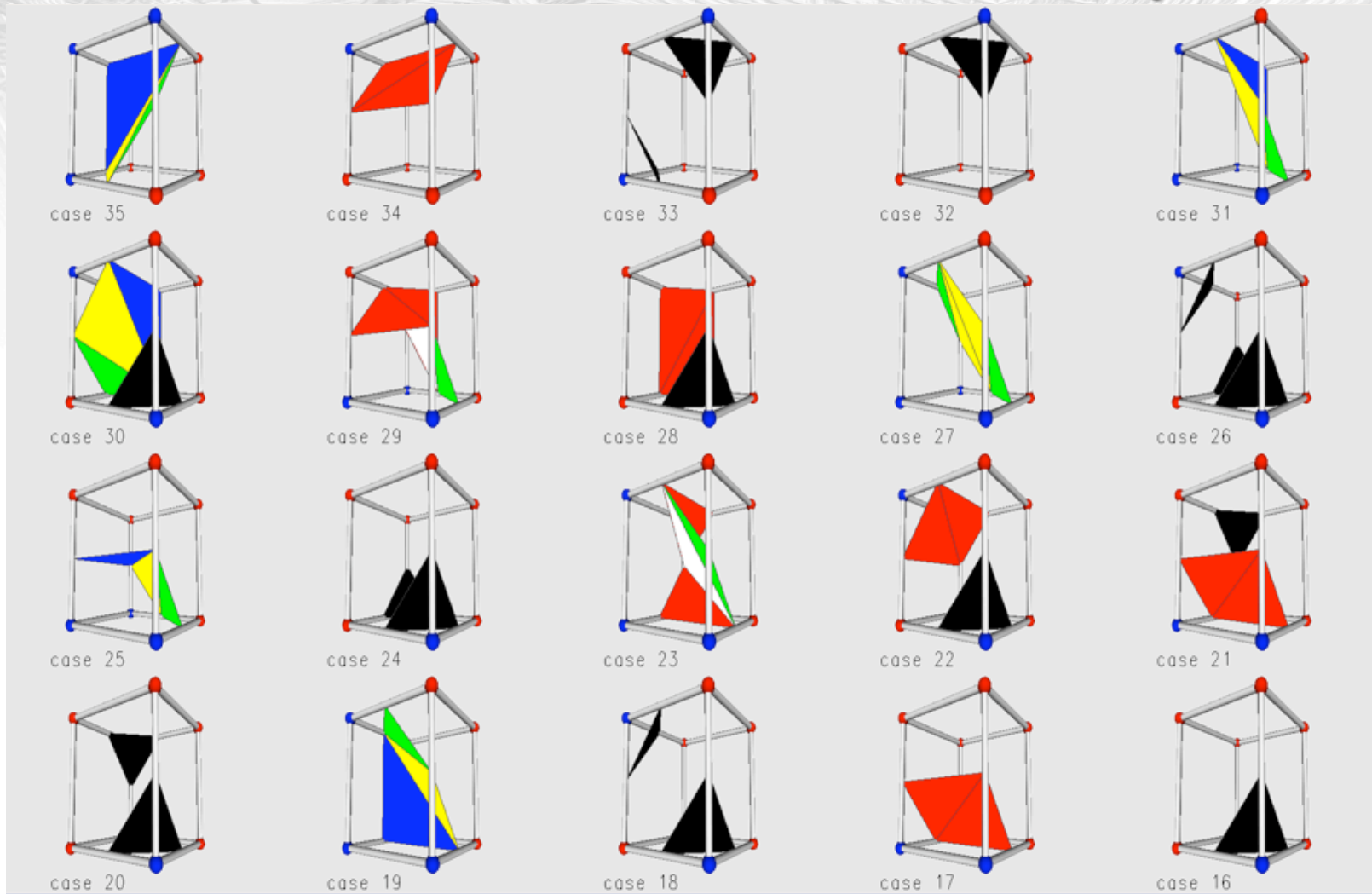


- True to the original Marching Cubes paper, we first did it by inspection too
- How ?

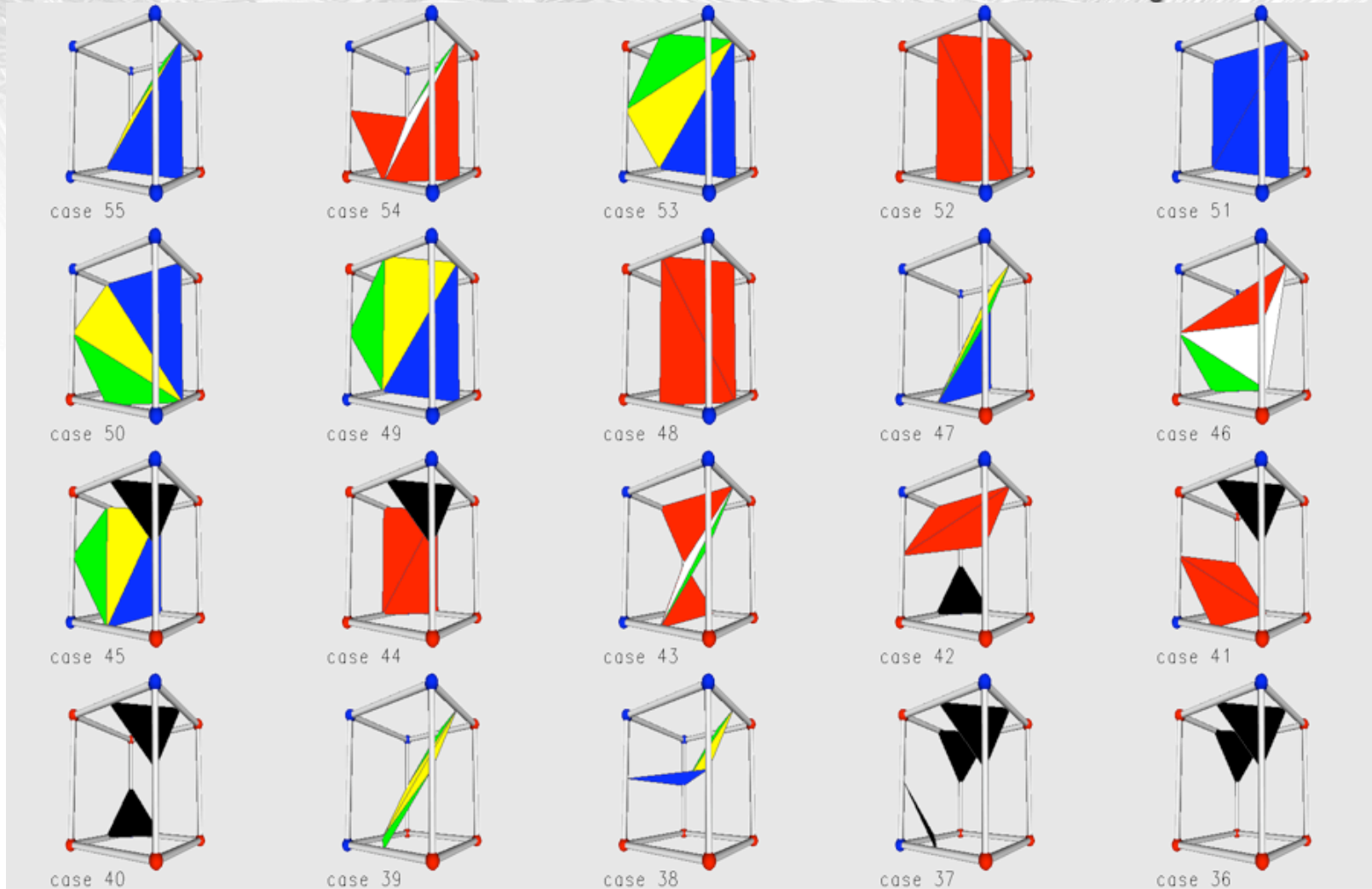
Edge Groups in the MC table



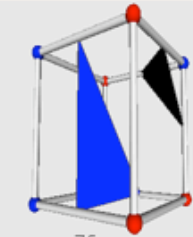
Edge Groups in the MC table



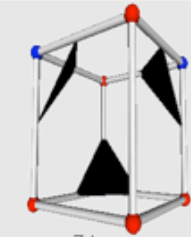
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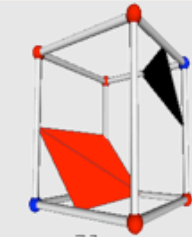
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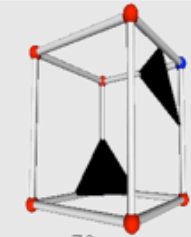
case 75



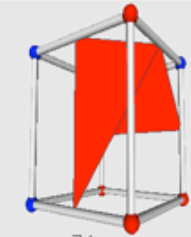
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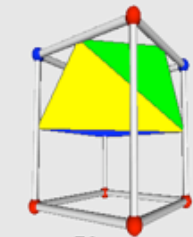
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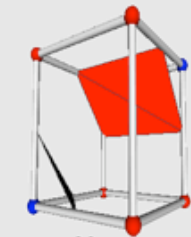
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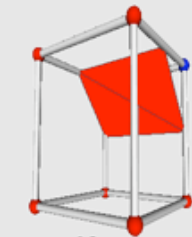
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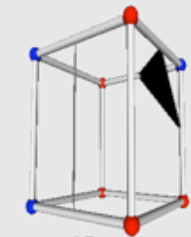
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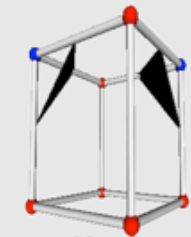
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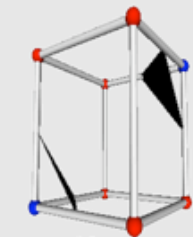
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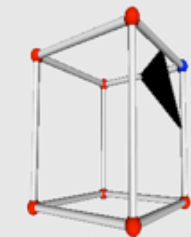
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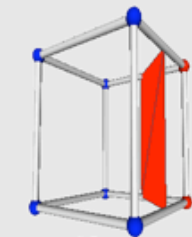
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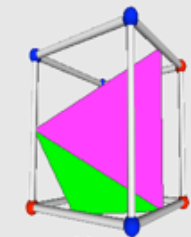
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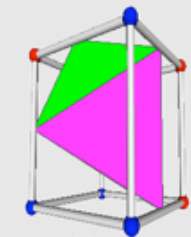
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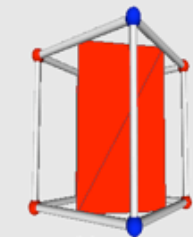
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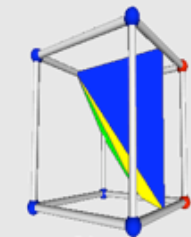
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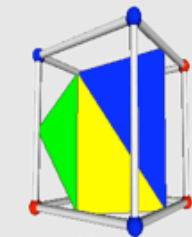
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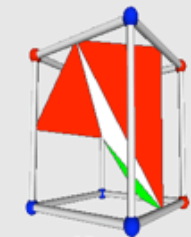
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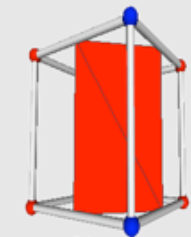
case 59



case 58

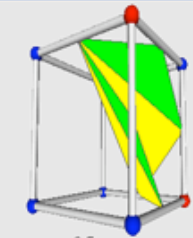


case 57

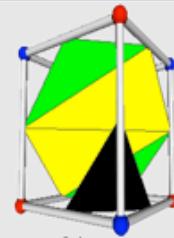


case 56

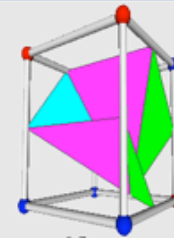
Edge Groups in the MC table



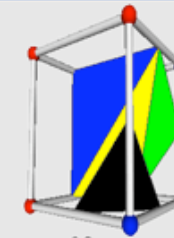
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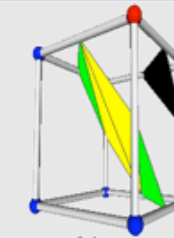
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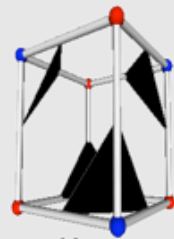
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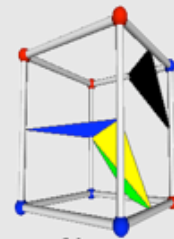
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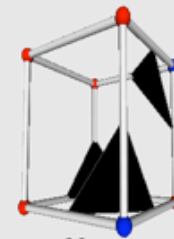
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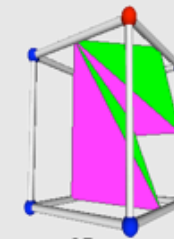
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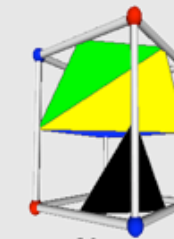
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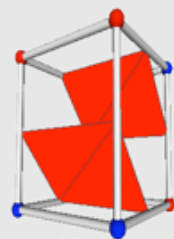
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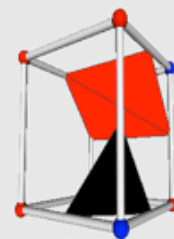
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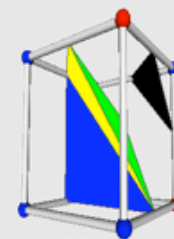
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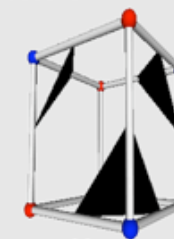
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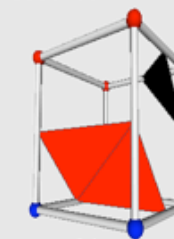
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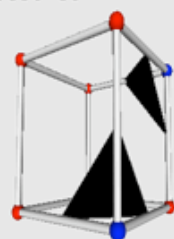
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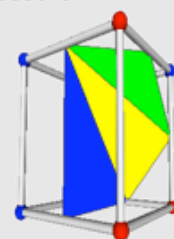
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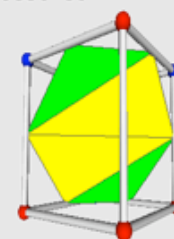
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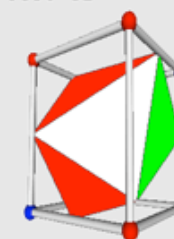
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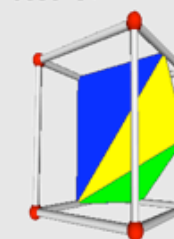
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case 78

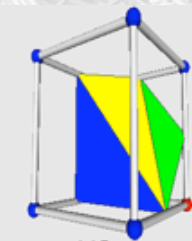


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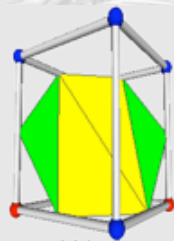


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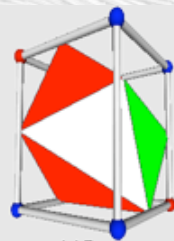
Edge Groups in the MC table



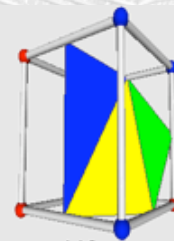
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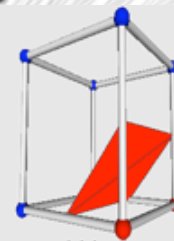
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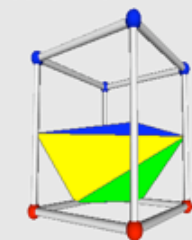
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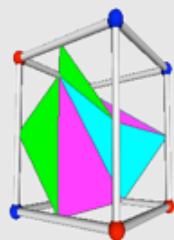
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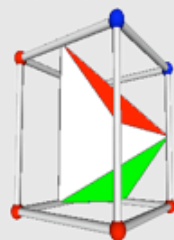
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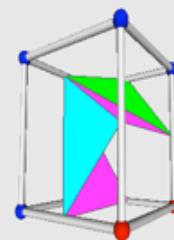
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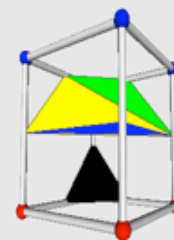
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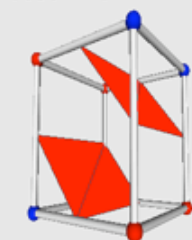
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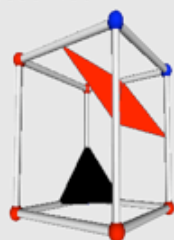
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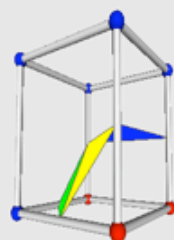
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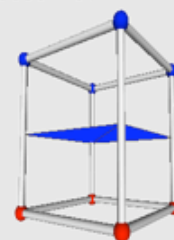
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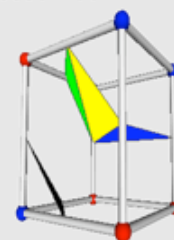
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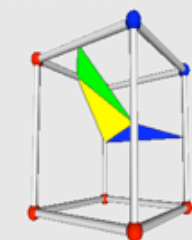
case 103



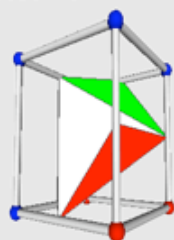
case 102



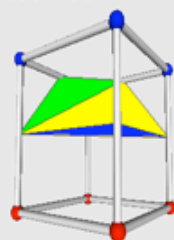
case 101



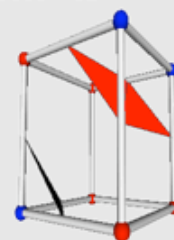
case 100



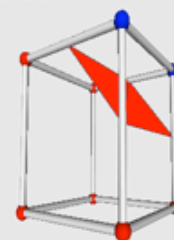
case 99



case 98

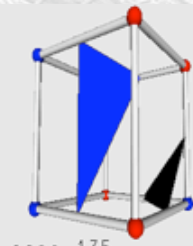


case 97

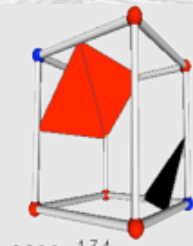


case 96

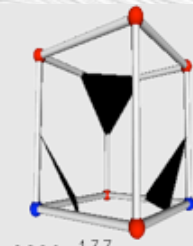
Edge Groups in the MC table



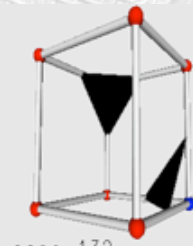
case 135



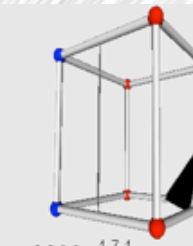
case 134



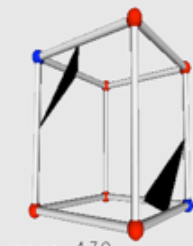
case 133



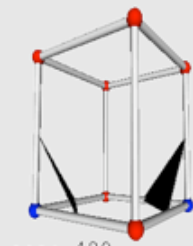
case 132



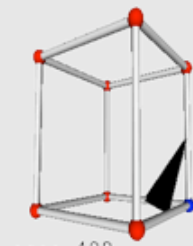
case 131



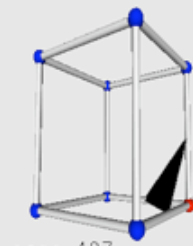
case 130



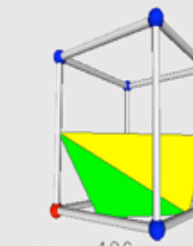
case 129



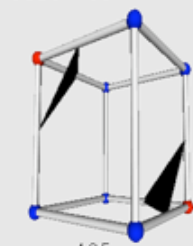
case 128



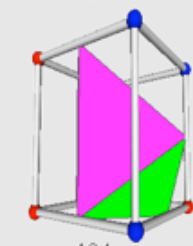
case 127



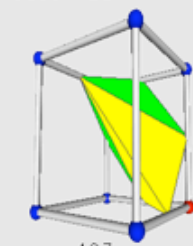
case 126



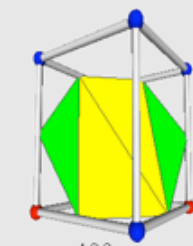
case 125



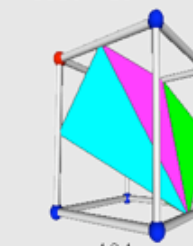
case 124



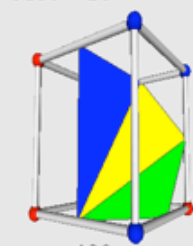
case 123



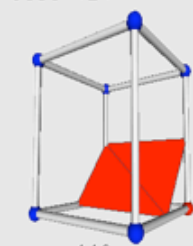
case 122



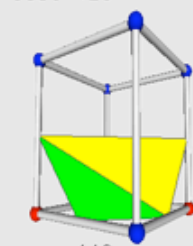
case 121



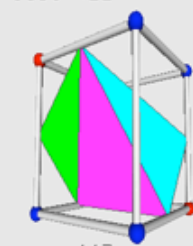
case 120



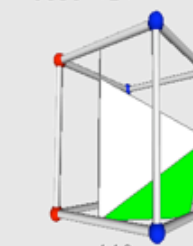
case 119



case 118

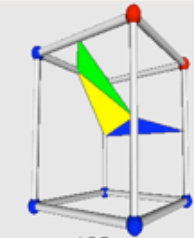


case 117

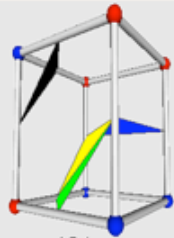


case 116

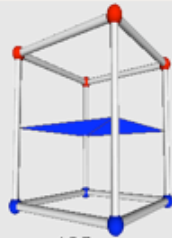
Edge Groups in the MC table



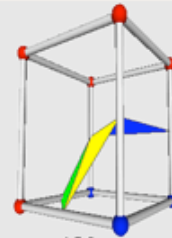
case 155



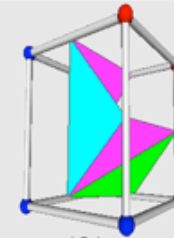
case 154



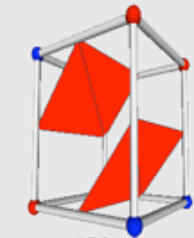
case 153



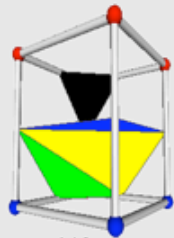
case 152



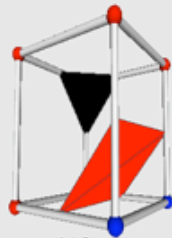
case 151



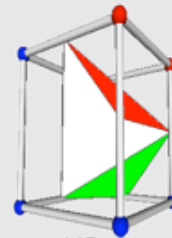
case 150



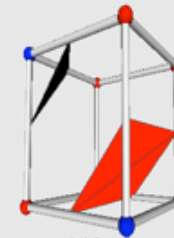
case 149



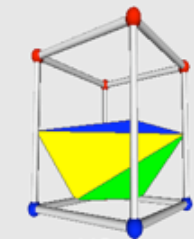
case 148



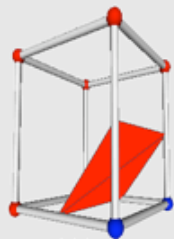
case 147



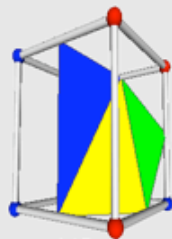
case 146



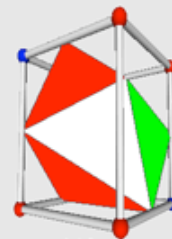
case 145



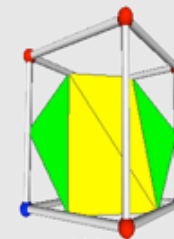
case 144



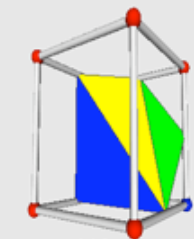
case 143



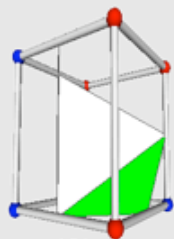
case 142



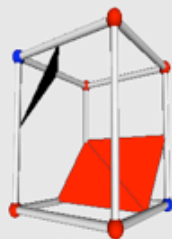
case 141



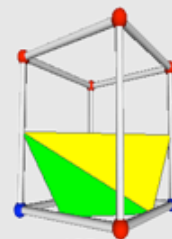
case 140



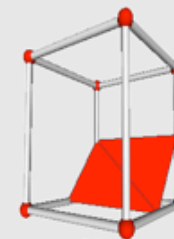
case 139



case 138

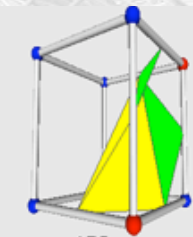


case 137

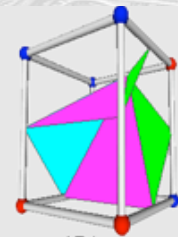


case 136

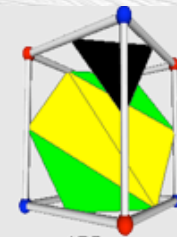
Edge Groups in the MC table



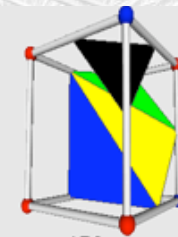
case 175



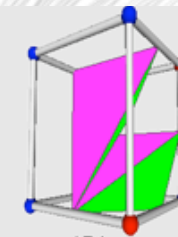
case 174



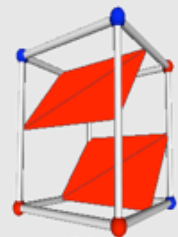
case 173



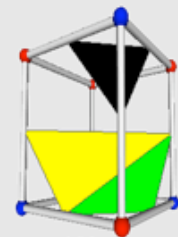
case 172



case 171



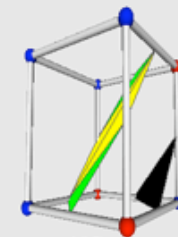
case 170



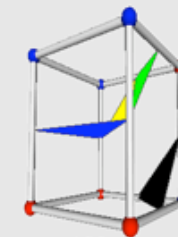
case 169



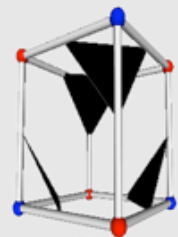
case 168



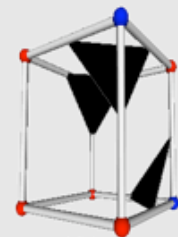
case 167



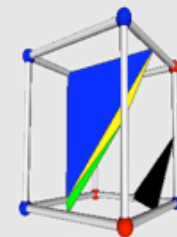
case 166



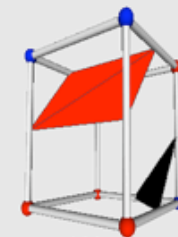
case 165



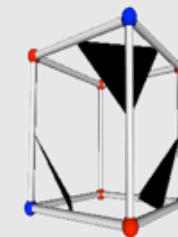
case 164



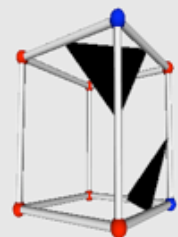
case 163



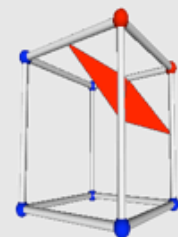
case 162



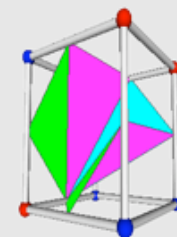
case 161



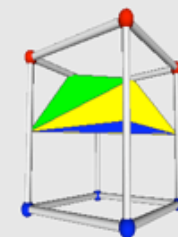
case 160



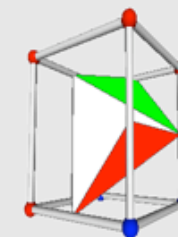
case 159



case 158

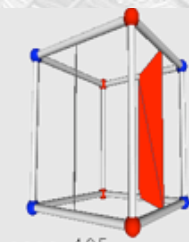


case 157

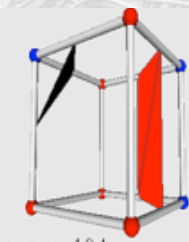


case 156

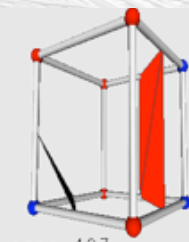
Edge Groups in the MC table



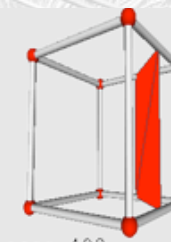
case 195



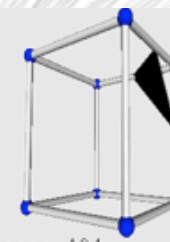
case 194



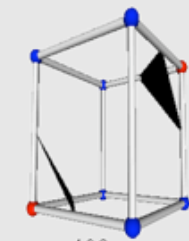
case 193



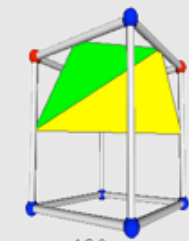
case 192



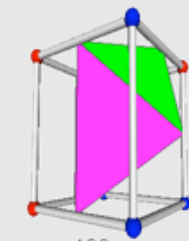
case 191



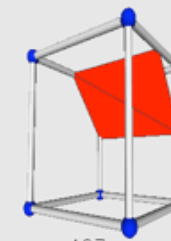
case 190



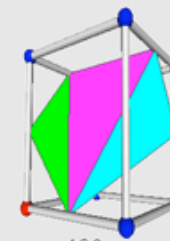
case 189



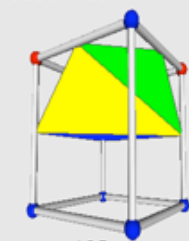
case 188



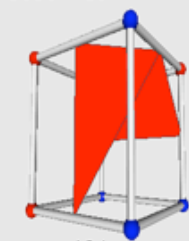
case 187



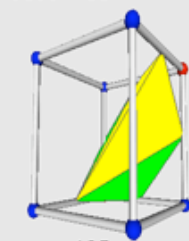
case 186



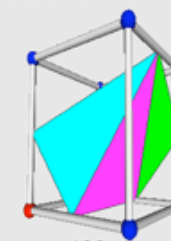
case 185



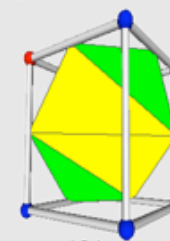
case 184



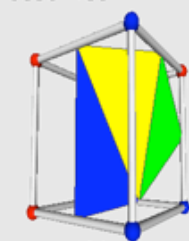
case 183



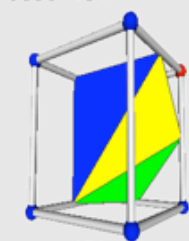
case 182



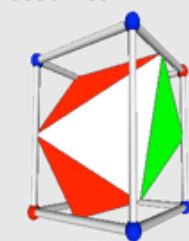
case 181



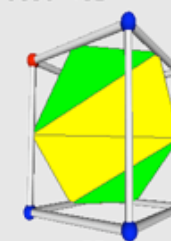
case 180



case 179



case 178

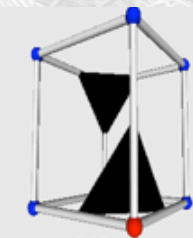


case 177

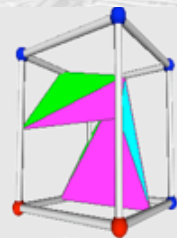


case 176

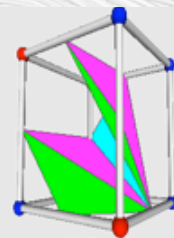
Edge Groups in the MC table



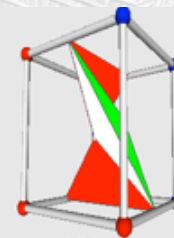
case 235



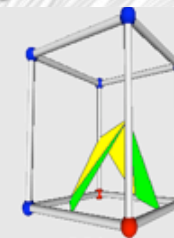
case 234



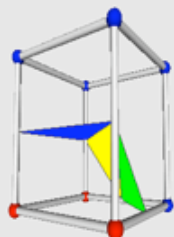
case 233



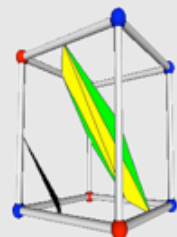
case 232



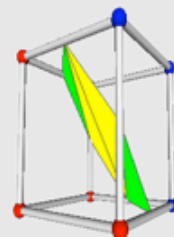
case 231



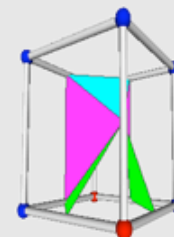
case 230



case 229



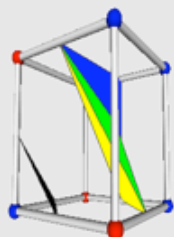
case 228



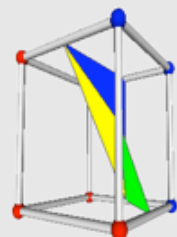
case 227



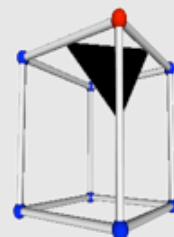
case 226



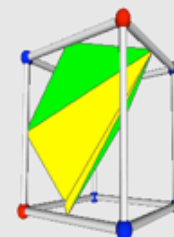
case 225



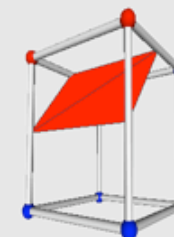
case 224



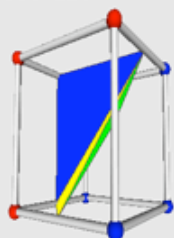
case 223



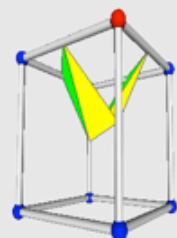
case 222



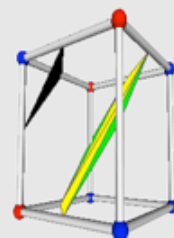
case 221



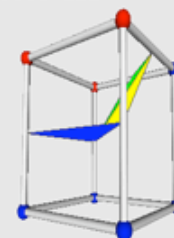
case 220



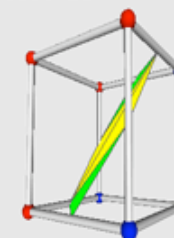
case 219



case 218

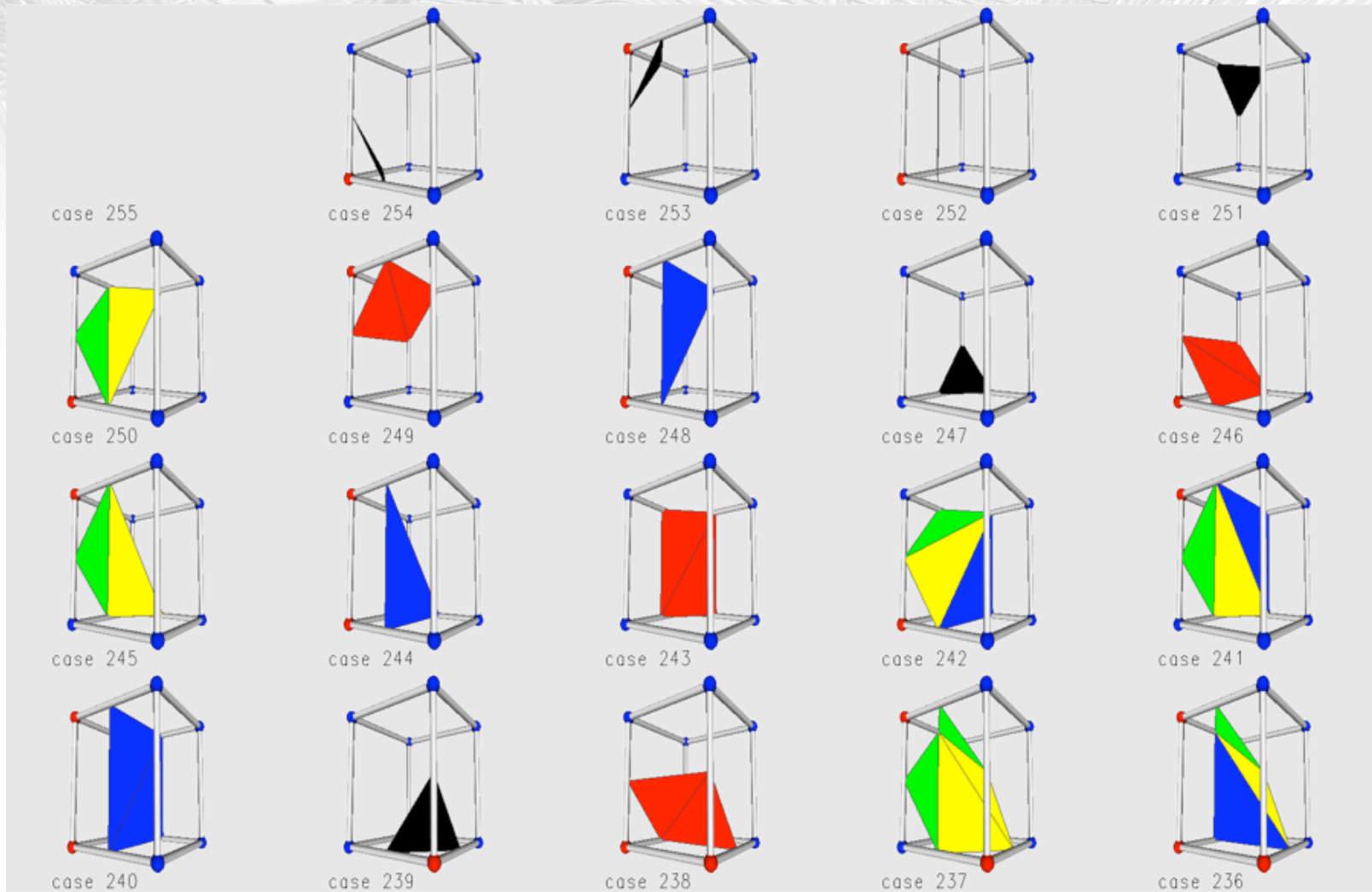


case 217

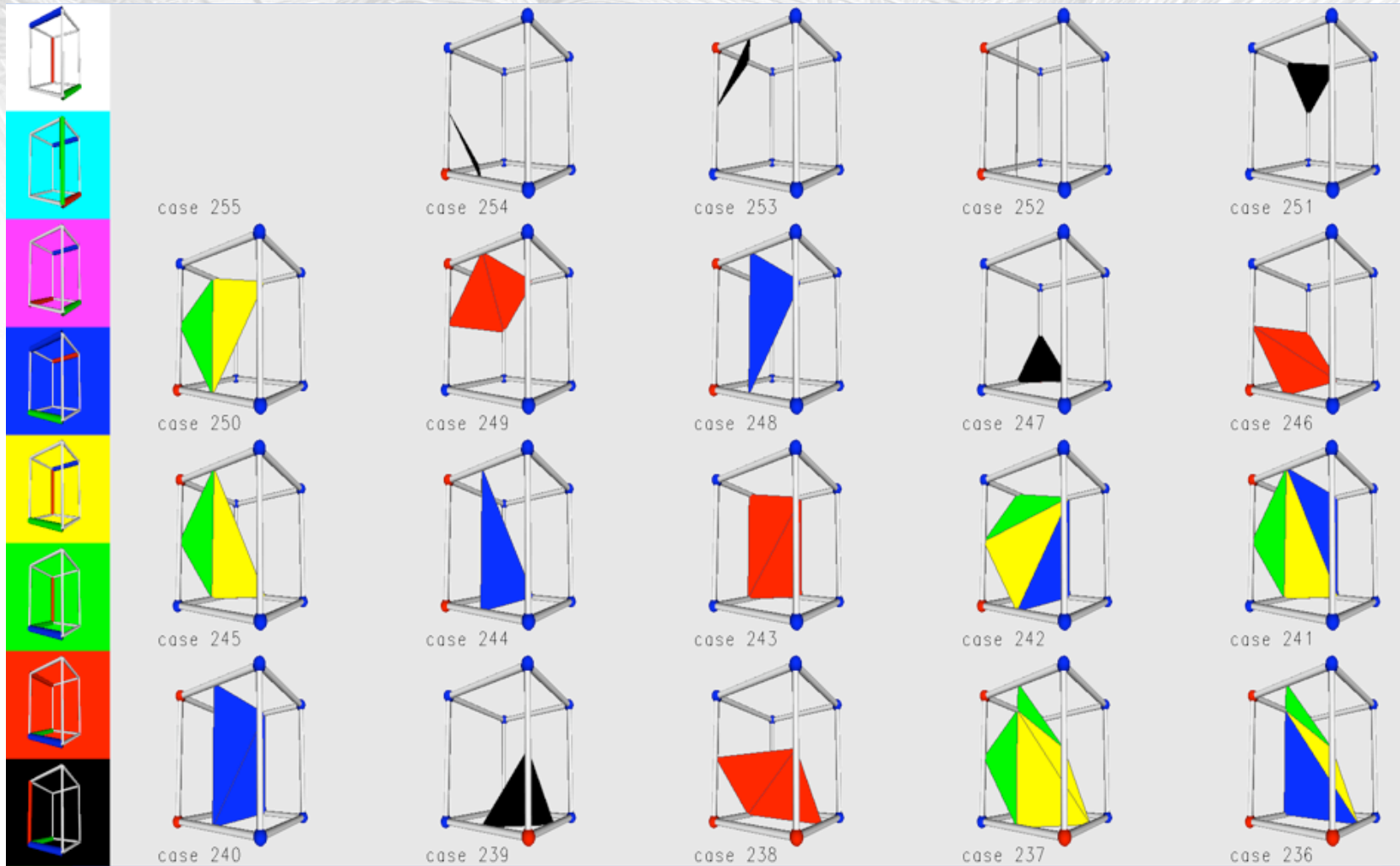


case 216

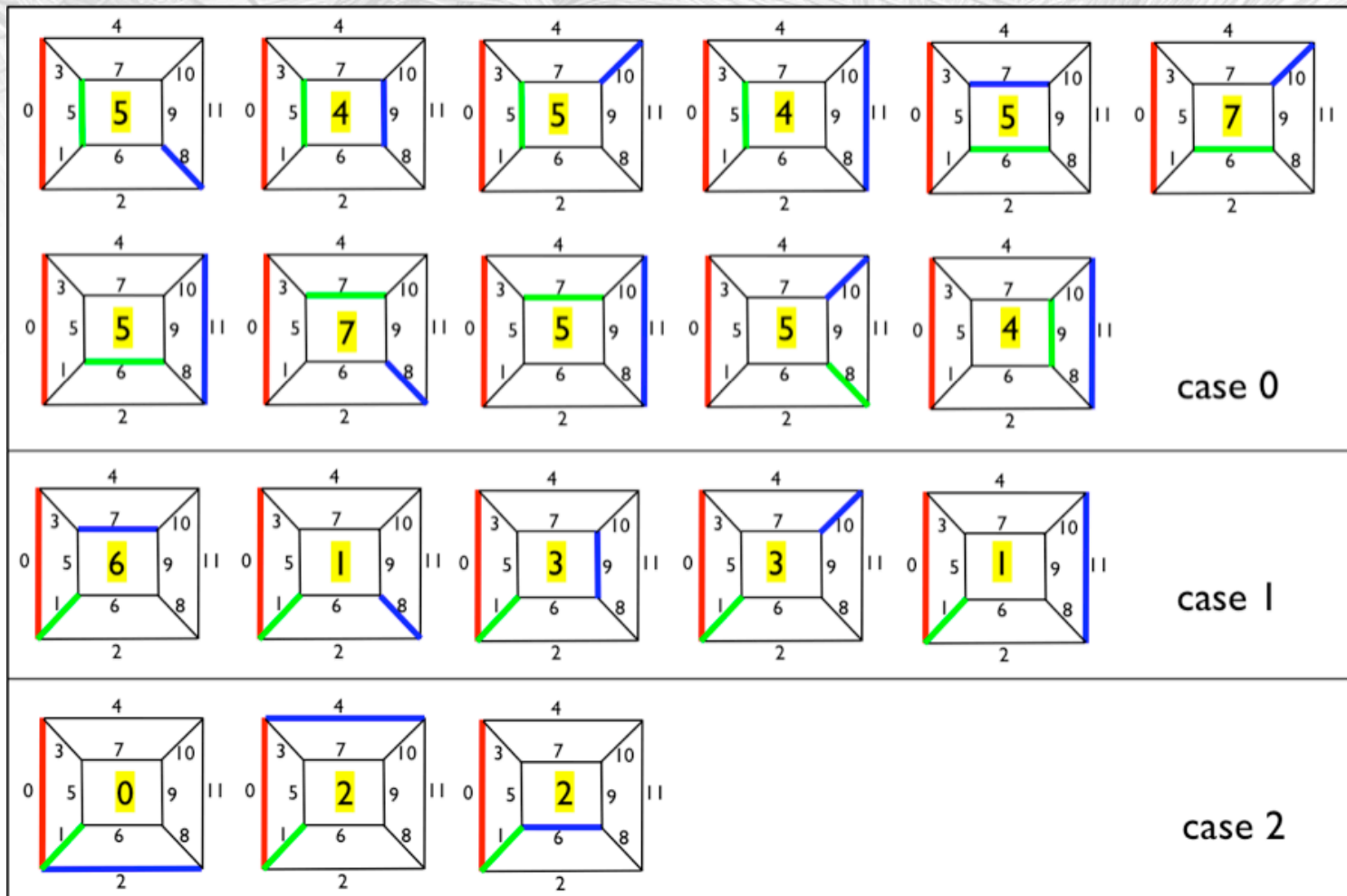
Edge Groups in the MC table



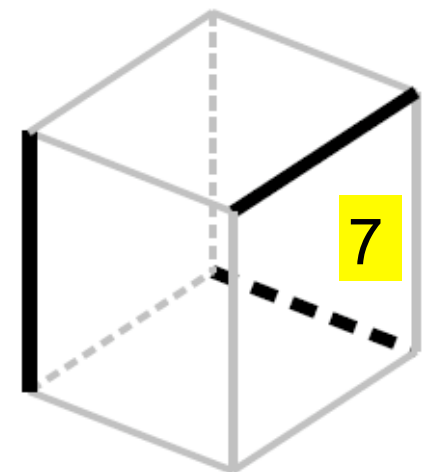
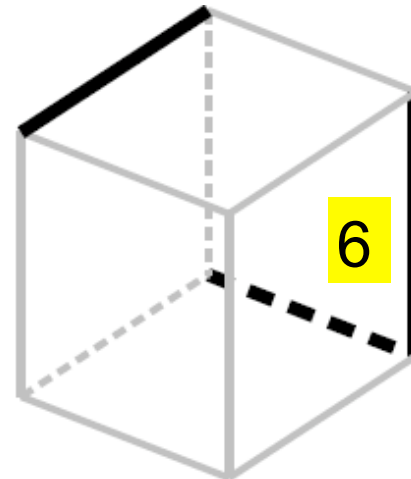
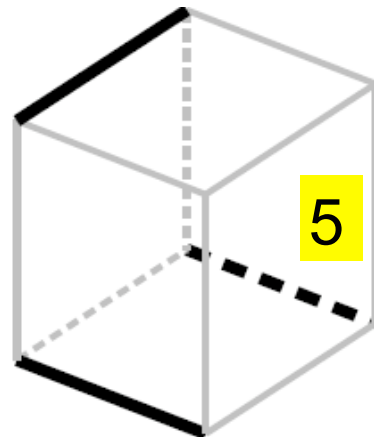
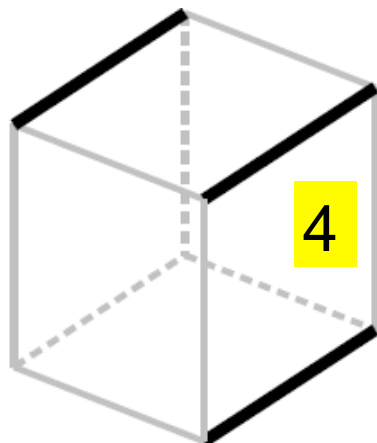
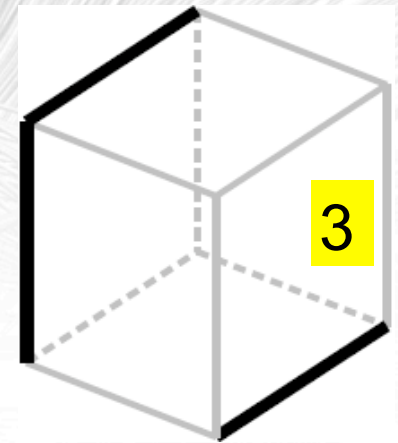
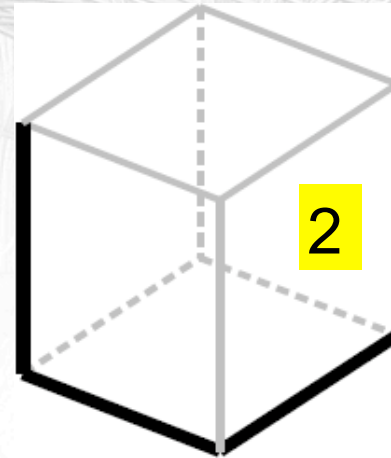
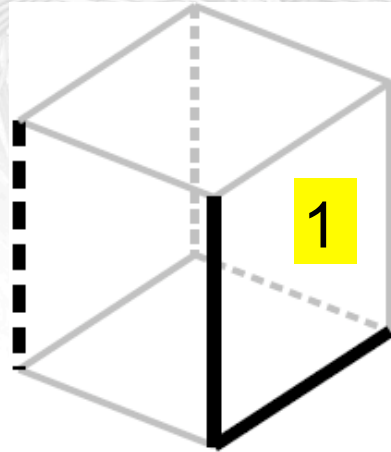
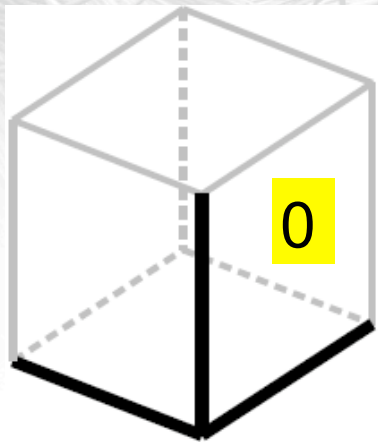
Edge Groups in the MC table



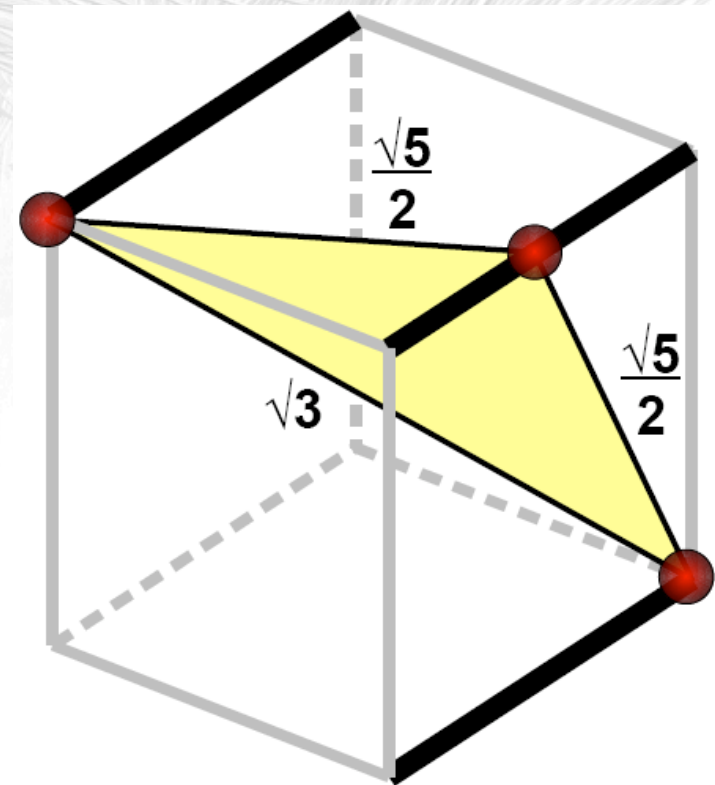
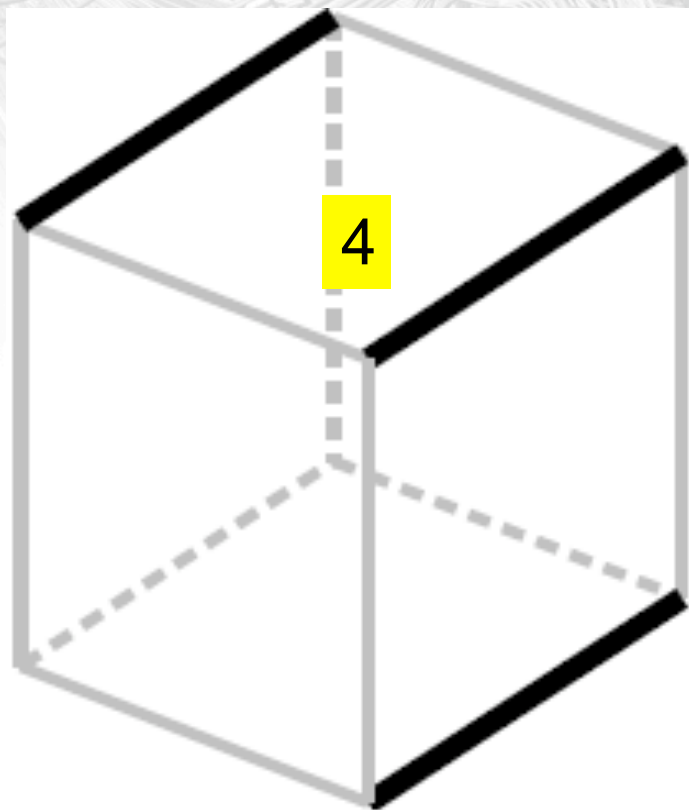
Edge Groups proof (paper)



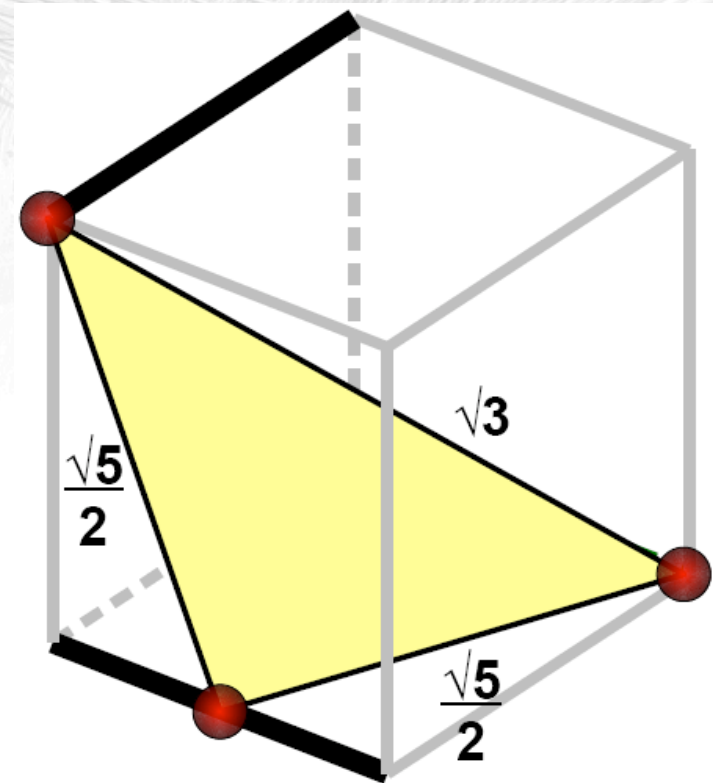
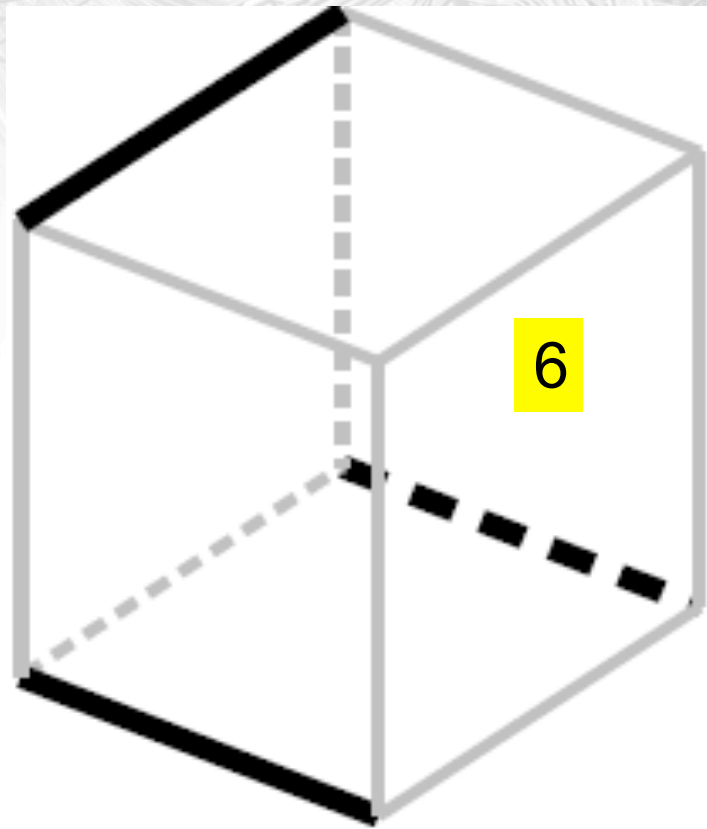
8 Edge Groups in Cubic Cells



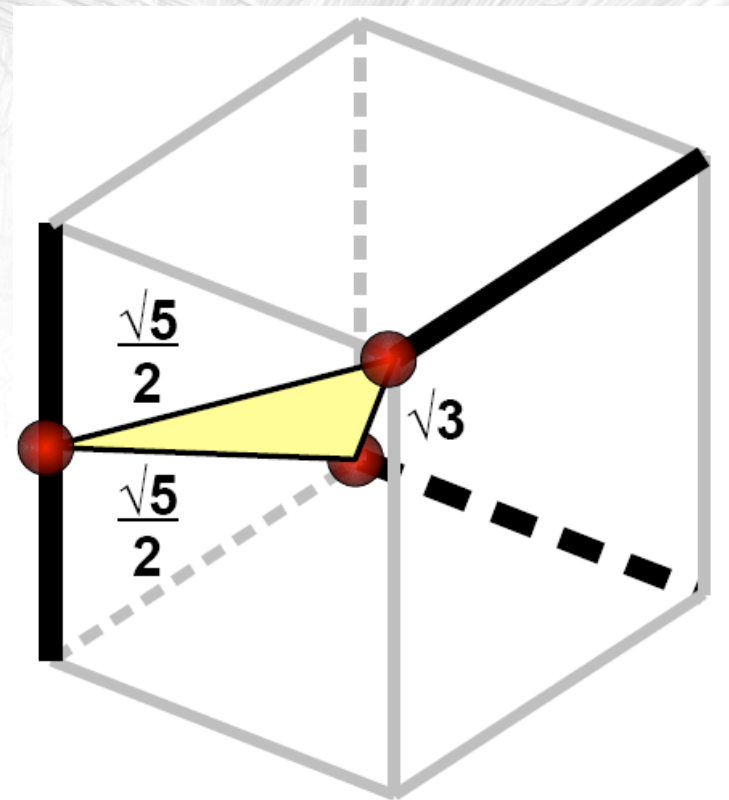
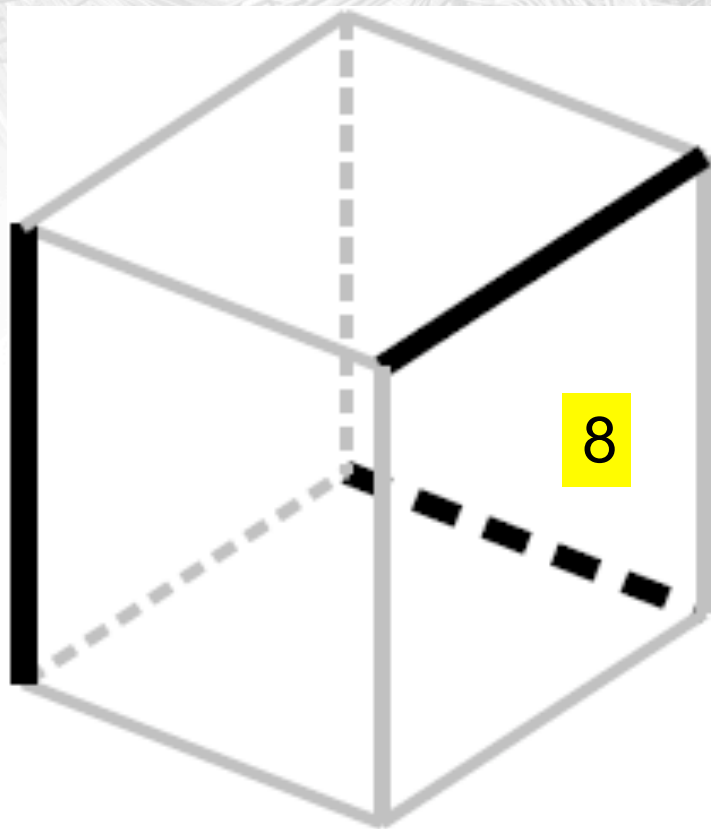
Triangle quality analysis: Worst triangle of case 4



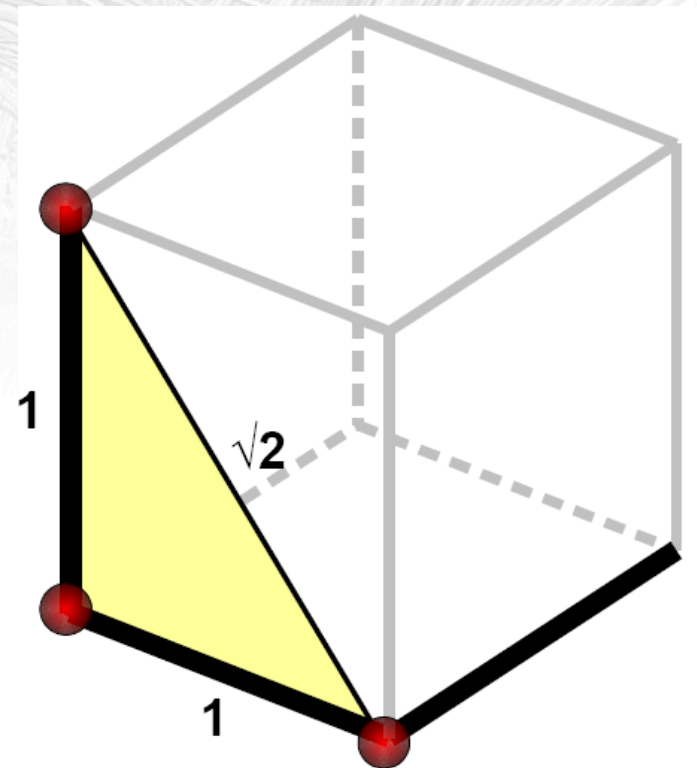
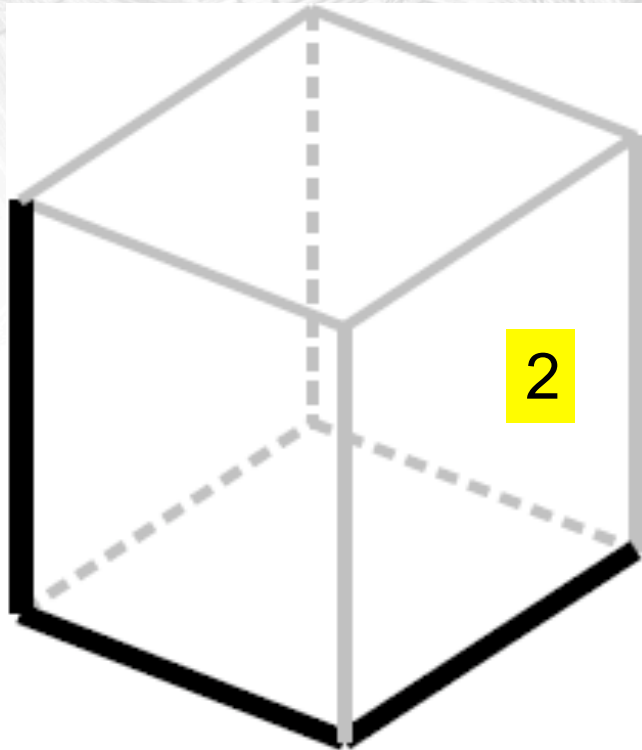
Triangle quality analysis: Worst triangle of case 6



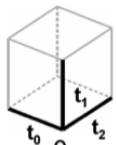
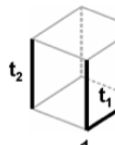
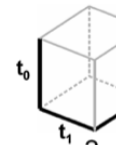
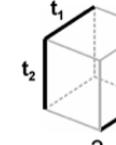
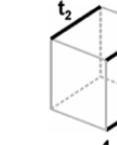
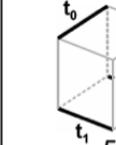

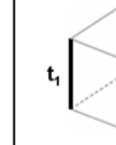
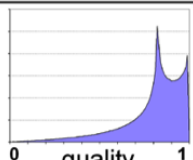
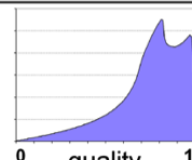

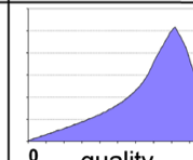
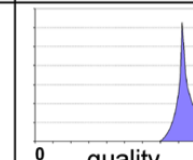
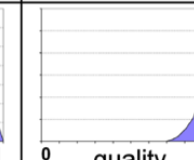
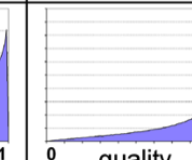

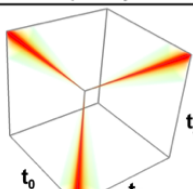
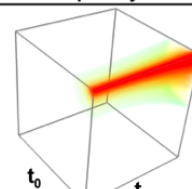
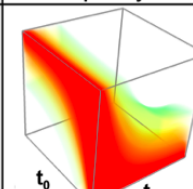
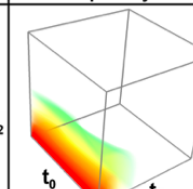
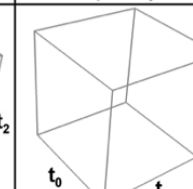
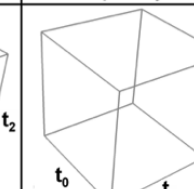
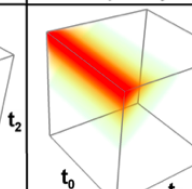
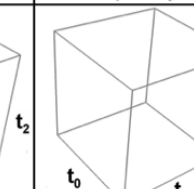
Triangle quality analysis: Worst triangle of case 8



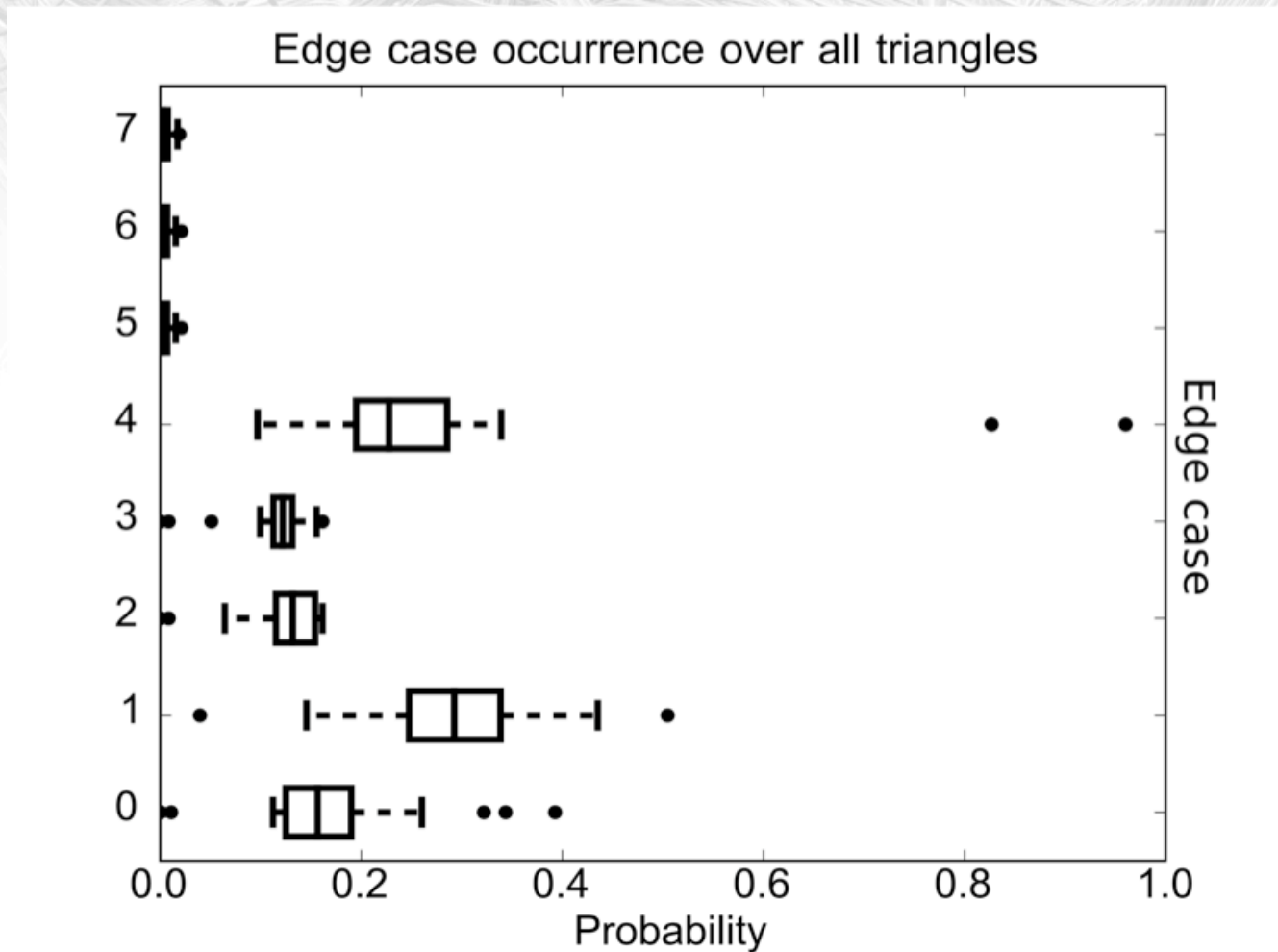
Triangle quality analysis: Best triangle of case 2



Triangle Quality Analysis: Edge Groups

Quality	Edge Groups							
								
<i>min/max</i>	0.0/1.0	0.0/1.0	0.0/0.828	0.0/1.0	0.698/1.0	0.698/1.0	0.0/1.0	0.698/1.0
<i>histogram</i>								
<i>density of bad triangles</i>								

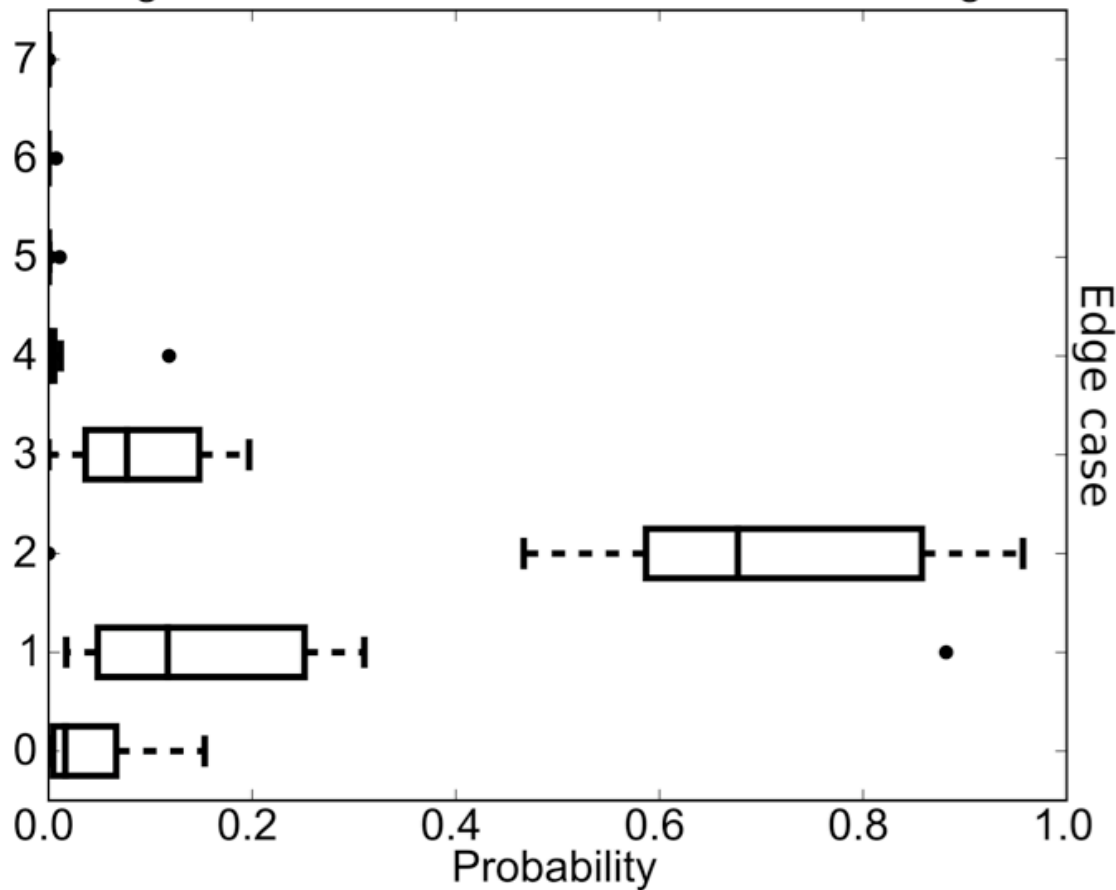
Edge Groups Occurrence



30 datasets

Interesting Observation: Edge Group 2 dominates

Edge case occurrence over worst 1000 triangles



30 datasets

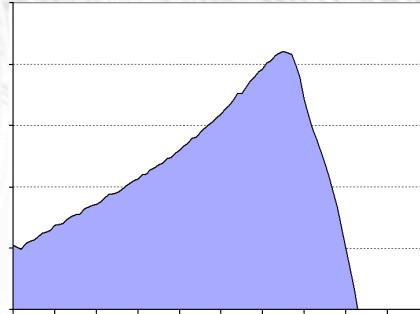
Outline



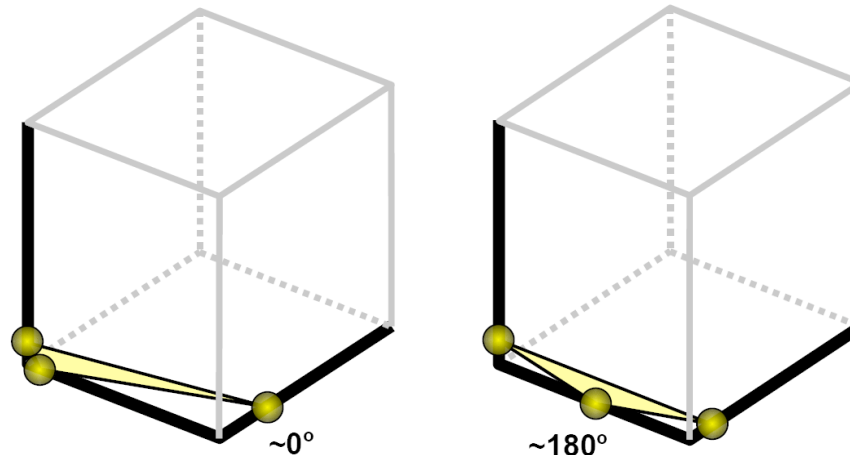
- Motivation
- Edge Groups in Cubic Cells
- **Improving Triangle Quality Based on Edge Groups**
- Results
- Conclusions

Improving Triangle Quality based on Edge Groups

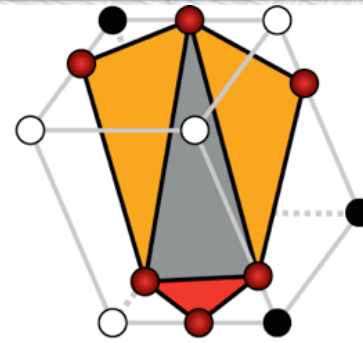
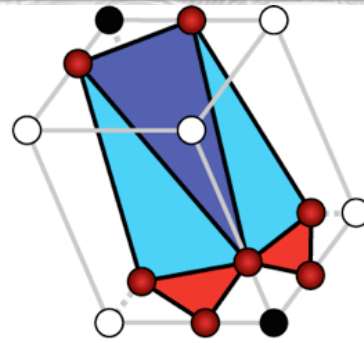
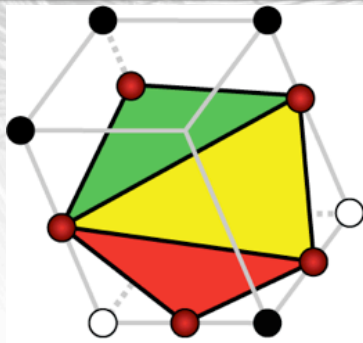
- Observation 1 : **Edge Group 2** generates the worst triangles
 - Changing the MC table



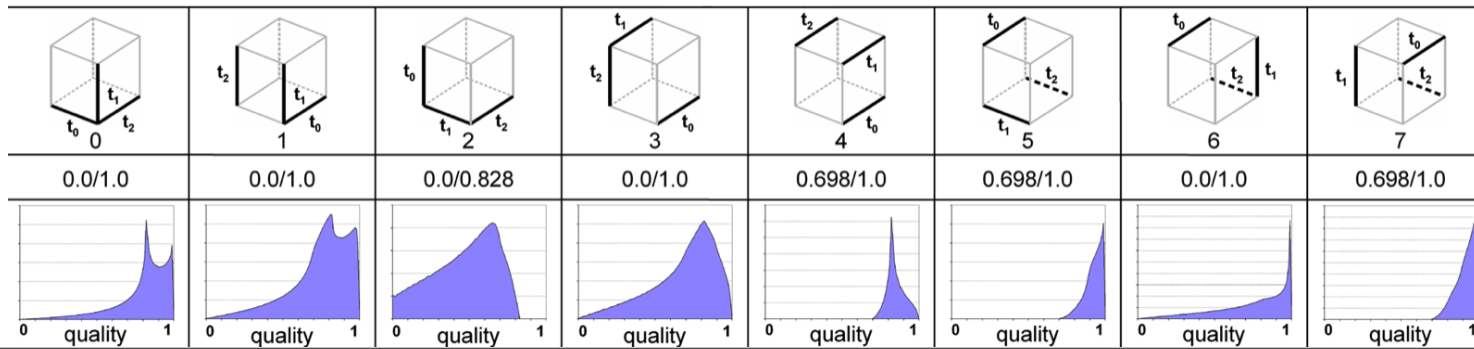
- Observation 2: **Bad triangles when isosurface is parallel to the edge**
 - Edge transformations using Macet [Dietrich et al 2009]



Improvement 1: Changing MC Table

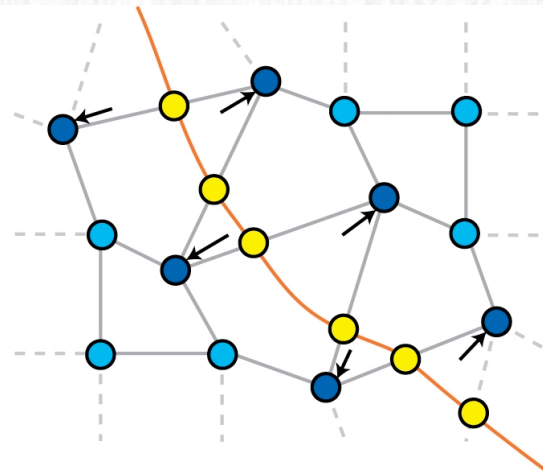
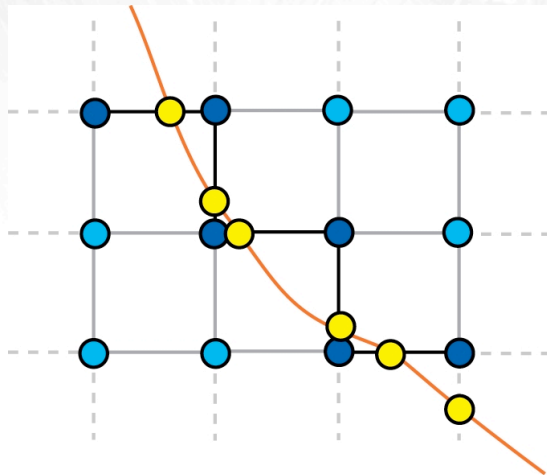


-  Group 1
-  Group 2
-  Group 3
-  Group 4
-  Group 5
-  Group 6
-  Group 7

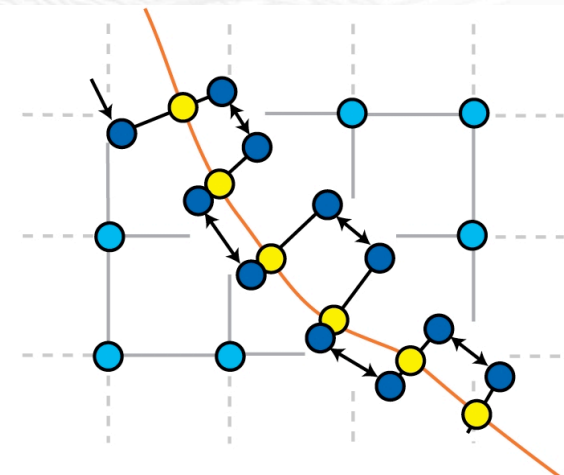


Improvement 2: Edge Transformations using Macet

- Macet [Dietrich et al 2009]
 - Edge transformations alter positions of grid points in MC



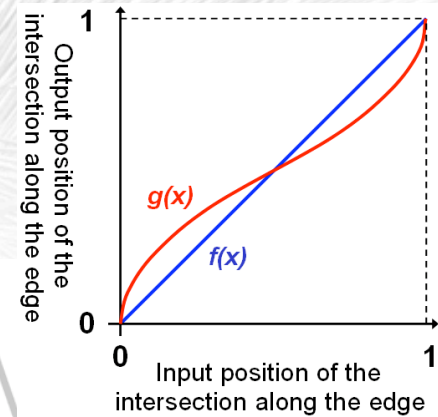
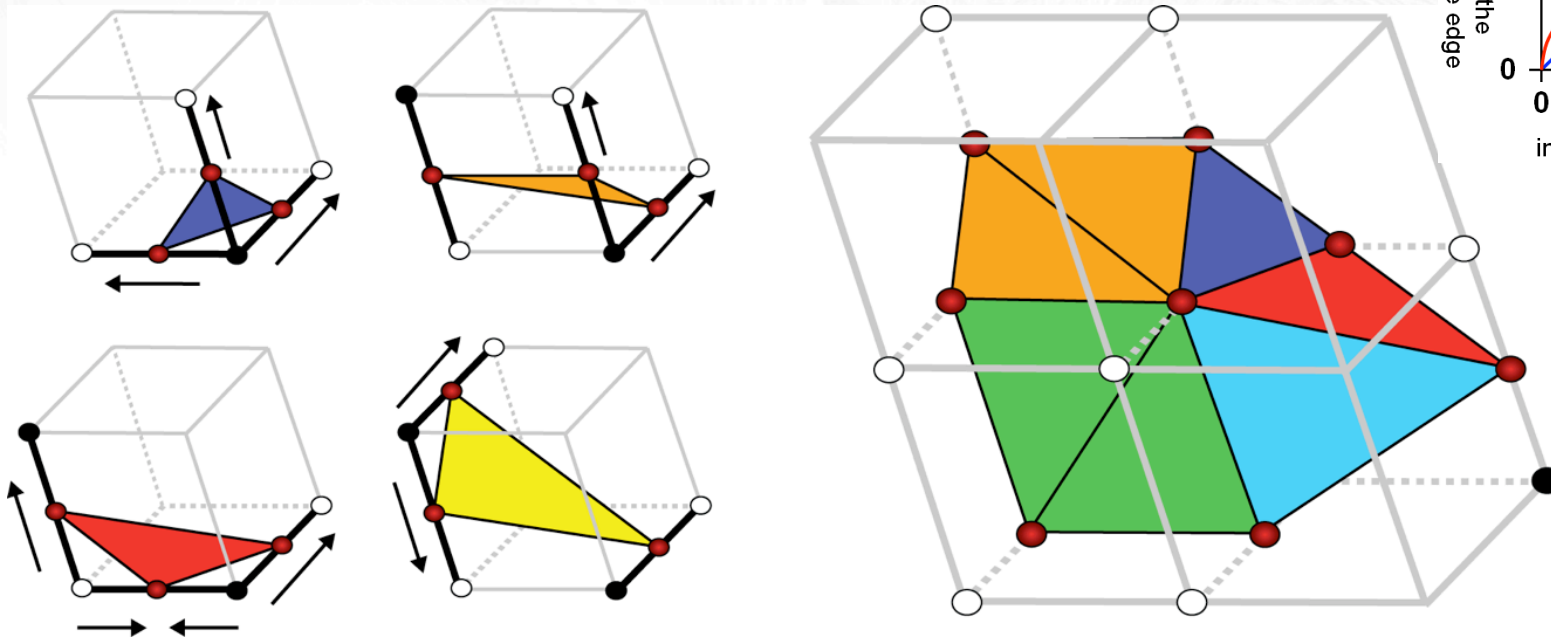
Gradient Transformation



Tangent Transformation

Improvement 2: Edge Transformations using Macet

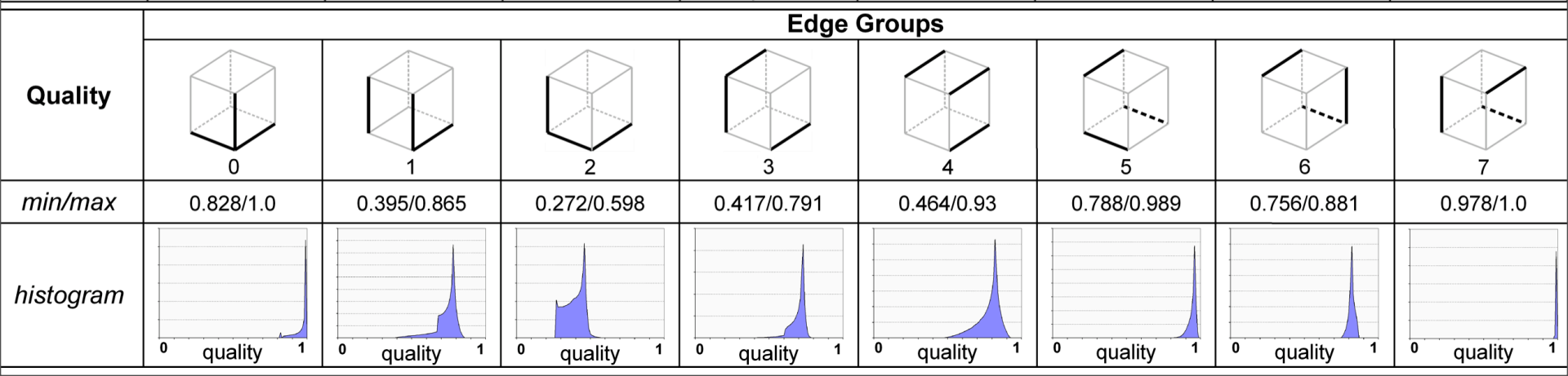
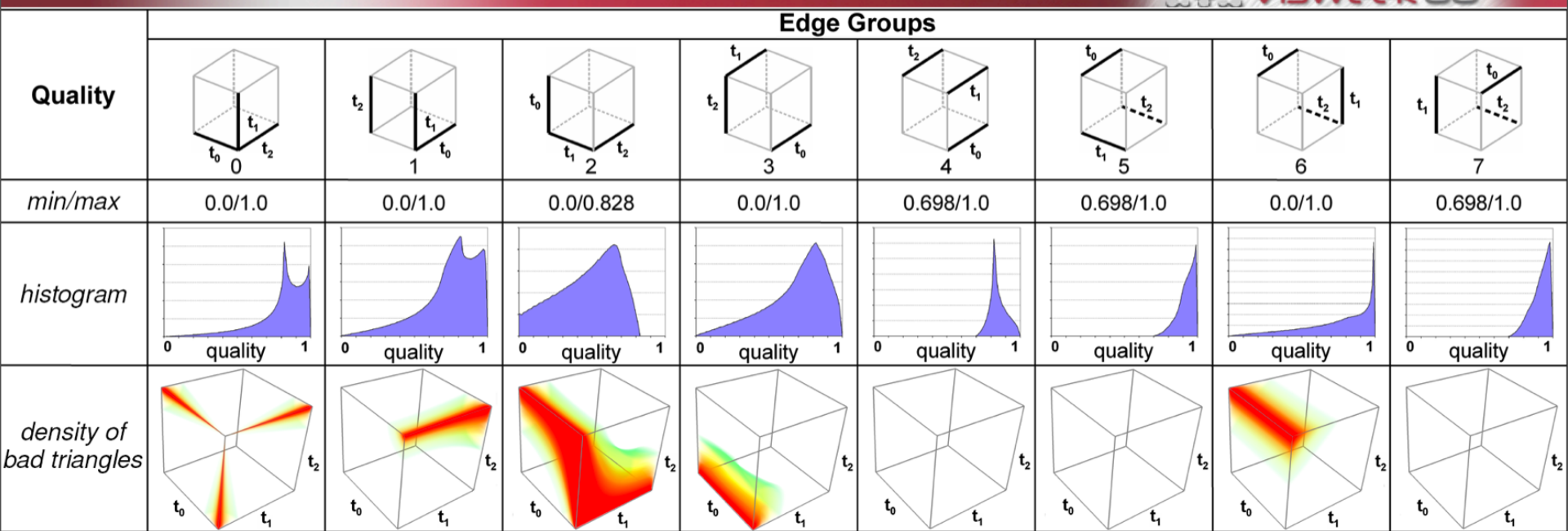
- Displacement of Intersection Vertices



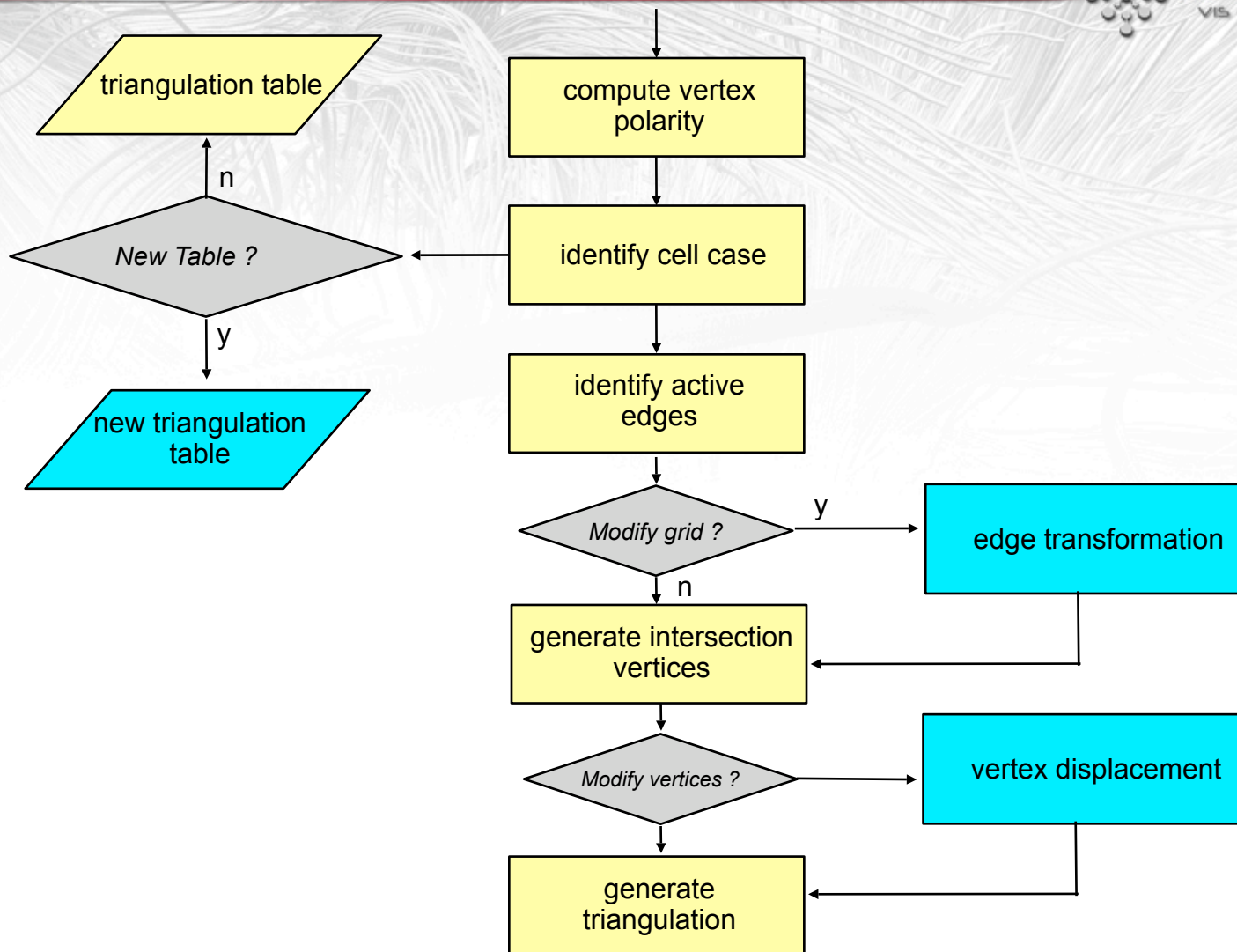
Improvement 2: Edge Transformations using Macet

	Edge Groups							
Quality								
<i>min/max</i>	0.0/1.0	0.0/1.0	0.0/0.828	0.0/1.0	0.698/1.0	0.698/1.0	0.0/1.0	0.698/1.0
<i>histogram</i>								
<i>density of bad triangles</i>								

Improvement 2: Edge Transformations using Macet



Summary of Changes to Marching Cubes Code



Outline



- Motivation
- Edge Groups in Cubic Cells
- Improving Triangle Quality Based on Edge Groups
- **Results**
- Conclusions

Results

	Original MC Old Table	Macet Old Table	Original MC New Table	Macet New Table Displacements
Silicium @ 140.5	0.00157			
Engine @ 49.5	0.00042			
Bonsai @ 49.5	0.00013			
Lobster @ 49.5	0.00088			

Results



	Original MC Old Table	Macet Old Table	Original MC New Table	Macet New Table Displacements
Silicium @ 140.5	0.00157		0.01792	
Engine @ 49.5	0.00042		0.00080	
Bonsai @ 49.5	0.00013		0.00152	
Lobster @ 49.5	0.00088		0.00153	

Results



	Original MC Old Table	Macet Old Table	Original MC New Table	Macet New Table Displacements
Silicium @ 140.5	0.00157	0.199	0.01792	
Engine @ 49.5	0.00042	0.235	0.00080	
Bonsai @ 49.5	0.00013	0.102	0.00152	
Lobster @ 49.5	0.00088	0.116	0.00153	

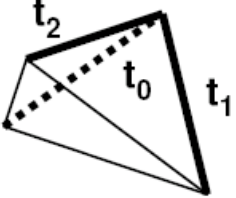
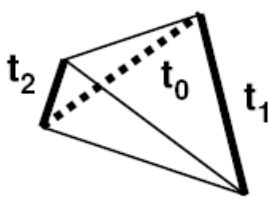
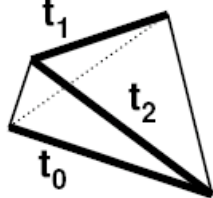
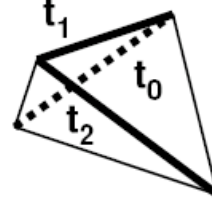
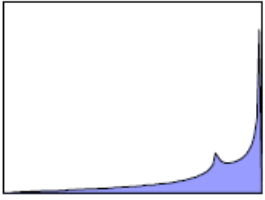
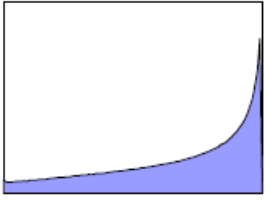
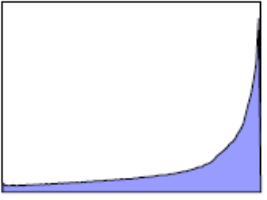
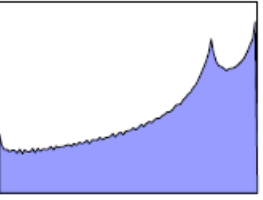
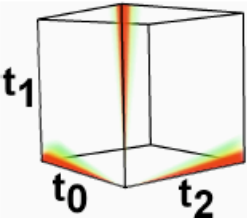
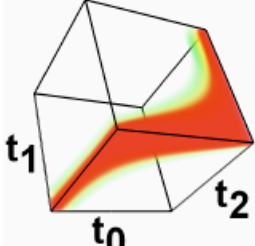
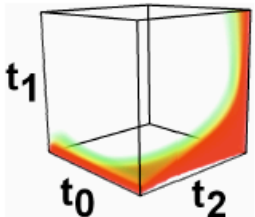
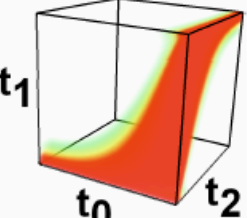
Results



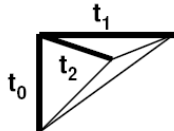
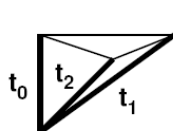
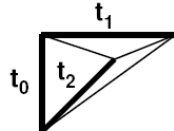
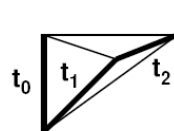
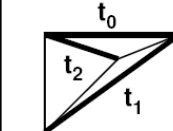
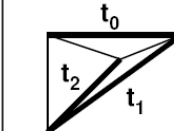
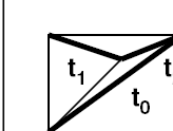
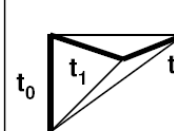
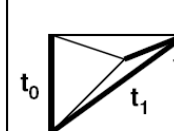
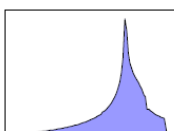
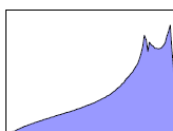
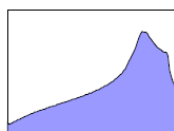
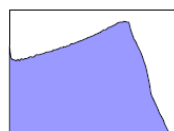
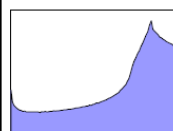
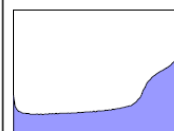
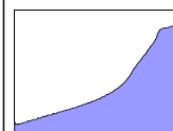
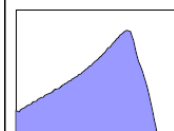
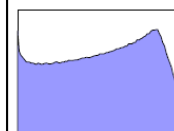
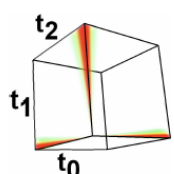
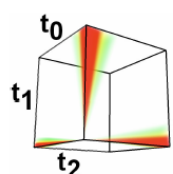
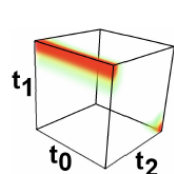
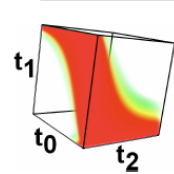
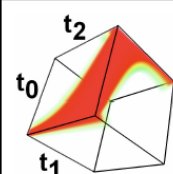
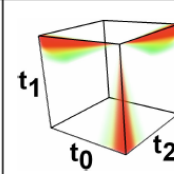
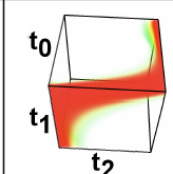
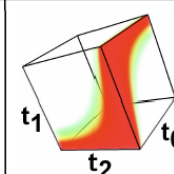
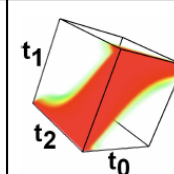
	Original MC Old Table	Macet Old Table	Original MC New Table	Macet New Table Displacements
Silicium @ 140.5	0.00157	0.199	0.01792	0.344
Engine @ 49.5	0.00042	0.235	0.00080	0.293
Bonsai @ 49.5	0.00013	0.102	0.00152	0.195
Lobster @ 49.5	0.00088	0.116	0.00153	0.247

Edge Groups in Tetrahedra Cells

- Extensions to tetrahedra cells **BCC Tetrahedra (4 Edge Groups)**

Quality	 0	 1	 2	 3
<i>min/max</i>	0.0/1.0	0.0/1.0	0.0/1.0	0.0/1.0
<i>histogram</i>	 0 quality 1	 0 quality 1	 0 quality 1	 0 quality 1
<i>density of bad triangles</i>	 t1 t0 t2	 t1 t0 t2	 t1 t0 t2	 t1 t0 t2

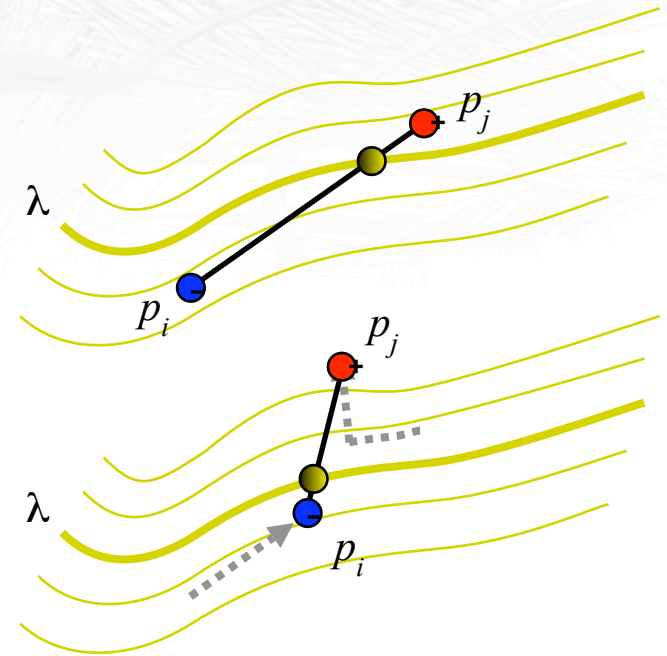
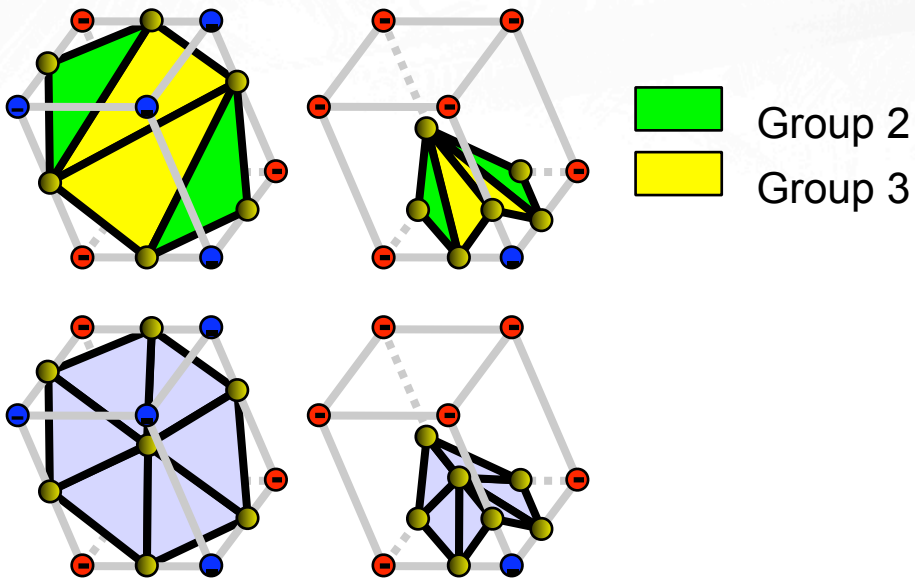
Edge Groups in Tetrahedra Cells

Quality									
	0	1	2	3	4	5	6	7	8
<i>min/max</i>	0/0.945	0.0/1.0	0.0/1.0	0/0.945	0.0/1.0	0.0/1.0	0.0/1.0	0/0.828	0/0.976
<i>histogram</i>									
	0 quality 1	0 quality 1	0 quality 1	0 quality 1	0 quality 1	0 quality 1	0 quality 1	0 quality 1	0 quality 1
<i>density of bad triangles</i>									
	t2 t1 t0	t0 t1 t2	t1 t0 t2	t0 t1 t2	t2 t0 t1	t1 t0 t2	t0 t1 t2	t1 t2 t0	t1 t2 t0

Kuhn Tetrahedra (9 Edge Groups)

Ongoing Work

- Unified Edge Transformations Macet (Technical Report coming soon)
 - Single Edge Transformation
 - Optional Vertex Displacement
 - More efficient, more quality



Latest Quality and Performance Results

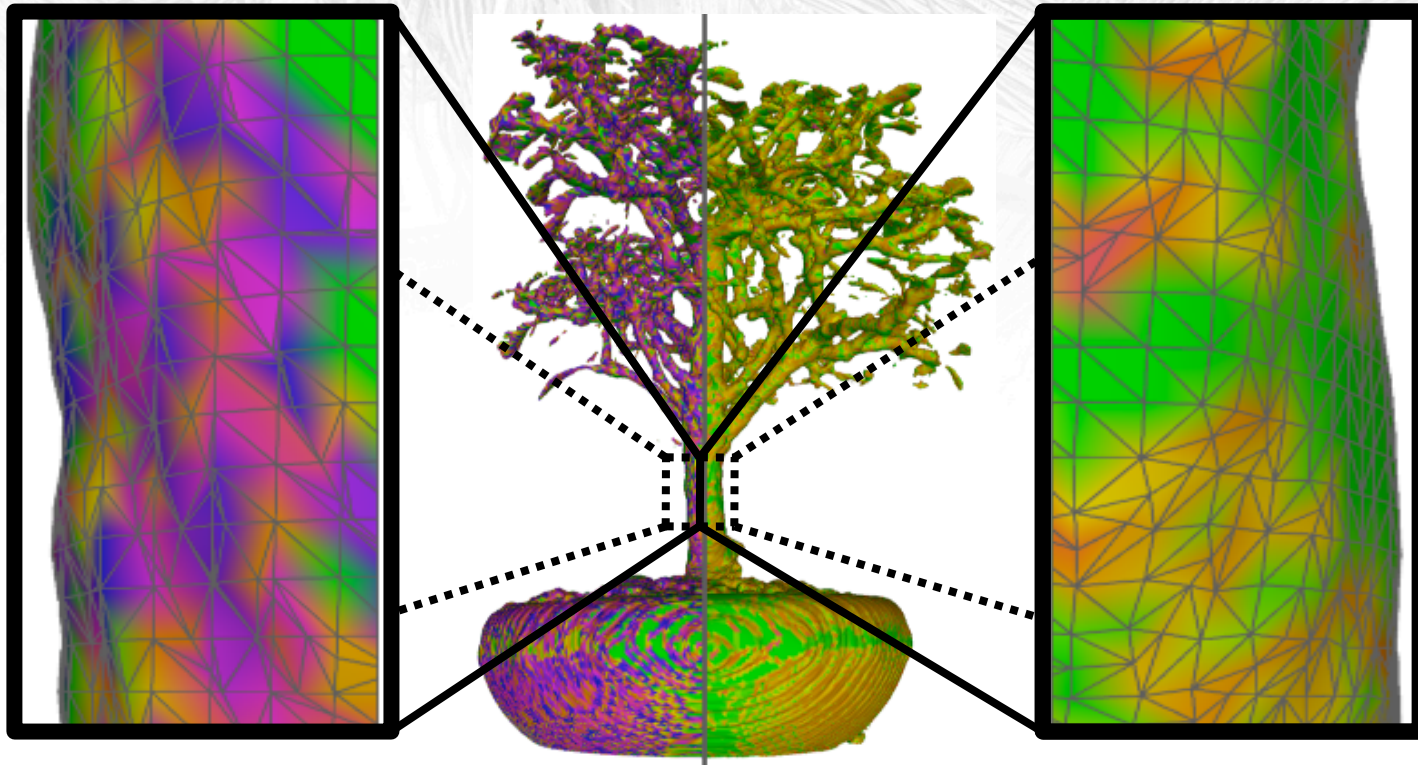


- Unified Edge Transformations Macet

	MC		Unified Macet	
	<i>time</i>	<i>quality</i>	<i>time</i>	<i>quality</i>
<i>Bonsai</i>	1.4	0.0002	9.9	0.32
<i>Engine</i>	1.1	0.0002	8.6	0.35
<i>Hydrogen</i>	0.15	0.069	0.7	0.52
<i>Laçador</i>	0.7	4.8e-7	2	0.37
<i>Neghip</i>	0.07	0.0031	0.64	0.38
<i>Siliicum</i>	0.03	0.0009	0.38	0.41

Demo

- Side-by-side comparison: MC x Unified Macet



Marching Cubes

Macet

Conclusions



- Main contributions:
 - Edge groups proposal and analysis in MC:
 - Histogram analysis of each individual case
 - Case 2 generates the worst triangles
 - Modifications in MC
 - Change of MC table
 - Improvements and Validation of Macet
 - Reproducibility (open source):
 - <http://www.sci.utah.edu/~cscheid/vis2008/edge-groups> (Vistrails)

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- IBM Faculty Awards (2005, 2006, and 2007)
- Reviewers for feedback

Questions ?

