Rapid Simplification of Multi-Attribute Meshes

Andrew Willmott
Maxis

HPG 2011

MAXIS

The Goal

MAXIS

Goal

MAXIS

Goal

≈10 ms

MAXIS

Why? Real-time Domain

- Need to generate LODs for player-created models
- Must generate them while the game is running interactively
- Other demands for CPU, including generating the original high-res mesh and textures

MAXIS

Domain

- Specific example:
  - Start a level
  - Ask server for player creations
  - Expand descriptions into model geometry and textures
  - Generate LODs
  - Display world and player creations

MAXIS

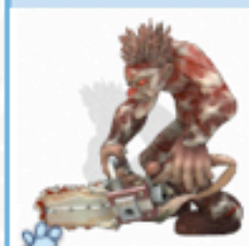

MAXIS

MAXIS


MAXIS

Spiked Drievesuct	Kordara	Oxytanum	Glarg	Blast
CopperLou	CopperLou	Himmelslaub	SSSarrati	75Fire1Dragon
				

Raviran	Chinese Dragon (F	Pyramander	Swesp	ALC_Shaggy Griff
Kuzuki	kiwi224	DudeMan95	Bokoo	fluxfrox
				

Shadow Triocular	Violent J	Adreux Empire	Bio-Mechanical Oı	Fantaiza Dragon
Cowboy_Cleatus	Hasmed	Cowboy_Cleatus	doozerdude	ViperialJoe
				

XMAS-dwarf Empi	Absol	Experiment 625	Pack Dragon	Triocular Scorpio
Chamäleon	LucarioGuy	RolandRyan	foreverpiping	95screenname13
				

MAXIS

Goldwing Gunship	The great Harves	Harpy	Galactic Lung Dra	Triocular Scorpio
MjrGlory	Kismet - Scar	CopperLou	AnUBISELEAsS	Parkaboy
				

Pinguis Viscus Spi	Triocular Scorpiod	gift for Ivonne	Night Rapton	Fineris
madnug	avaslash	RolandRyan	AnUBISELEAsS	RedDragon1958
				

Inarmi	Pink Unipeg	Shredder	Boba Fett	Triocular Scorpio
Dustpuppy111	AnUBISELEAsS	FritoPie	FritoPie	_Cepholapoid_
				

Half Chicken-Half	Announcement!	Arctic Lion	Medusa	Systrous, Galactic
75Fire1Dragon	Chamäleon	flamestar	CopperLou	BlackSheep6059
				

MAXIS

Charles Darwin	Triocular Scorpio	Phoenix	Triocular Scorpio	Peiniger
Svndl	Forrest93	AnUBISELEAsS	MaxisCactus	Himmelslaub
				
Groudon	**Kashmi**	**Groudon**	**Whispers**	**Restoreon**
d-rob604	Kemeiki	Antarcticas	DinoRexCM	CopperLou
				
Chicken Tank	**Ho-oh**	**Cerebrilith**	**Hive**	**Warrior Sackboy**
Sarsaparilla	lydiadragon	Bernini	TarsTarkas	Cowboy_Cleatus
				
Your The MASTER	**Alopid**	**Leireon**	**Celestial Dragon**	**Kyogre**
tacobob1	Kemeiki	CopperLou	Milly013	Antarcticas
				

MAXIS

Queen Bee	Einfin	Maintenance Drok	Spring Fling Annou	Ground Dragon
TarsTarkas	Himmelslaub	Parkaboy	TarsTarkas	Cowboy_Cleatus
				

Baba Yaga's Hous	Chinese Phoenix	Unterwasserwelt	Craby	Araya Armor Ripp
Slartibartfast38	AnUBISELEAsS	Chamäleon	sergio97	MjrGlory
				

Breloom	GIVE THE PATCH!	Chinese Cloud Dra	Emperor Auric'cli	Turteltaub
Antarcticas	Covest	AnUBISELEAsS	Simago624	Himmelslaub
				

Maker	Fafnir	Blue Lagoon	Frost Demon Scor	Dialeon
Falcore	CopperLou	Kevin92	doozerdude	Shadowklaw
				

MAXIS

Worked Example

- Generate 20 meshes x 3 LODs
- Say 10% of CPU per frame

- 10s per LOD -> 1 hour 40 minutes
- 10 seconds -> 16 ms per LOD

MAXIS

Other requirements

- Robustness
  - Player-created meshes, not artist-created
  - No time for input cleanup passes
- Static LODs
  - Need to LOD shaders and animation too
  - Generate lowest LODs first
- GPU-friendly simplification

MAXIS

Previous Work

- Rossignac & Borrel [1993]
- Hoppe, Garland & Heckbert [1996-8]
- Out of core: Lindstrom [2000]
  - Massive meshes without thrashing
  - Vertex clustering and quadrics
- DeCoro & Tatarchuk [2007]
  - Vertex Clustering on GPU

MAXIS

Why not QEM + Edge Collapse?

- First thing we tried
- Simply couldn't get it fast enough
  - Sequence of serial operations
  - Poor memory access patterns
- Requires triangle connectivity
- Requires collection of manifold surfaces

MAXIS

Vertex Clustering

- Older, less sophisticated technique
- Very fast, very simple, very robust
- Quality not as good as edge-collapse-based algorithms

MAXIS

Vertex Clustering

- Enclose model with a uniform grid
- Cluster vertices inside cells
- Remap vertex indices according to cells
  - Store unique index in grid
  - OR use virtual grid: hash map lookup on cell i,j,k

MAXIS

Vertex Clustering

- For all vertices:
  - Classify by containing grid cell
  - Accumulate representative cell position
- For all triangles:
  - Update vertex indices according to cell
  - Discard if degenerate
- Compact mesh

MAXIS

Vertex Clustering Advantages

- Fast on modern architectures
  - Doesn't require edge connectivity
  - Good memory coherency as Lindstrom demonstrated
  - Two linear passes: vertices then indices
- Robust
  - Will take absolutely any mesh you throw at it

MAXIS

LOD for GPU

- Lots of small triangles are bad
  - triangle setup
  - Sliver triangles also bad
- Traditional simplification focuses on preserving detail
- Better: match triangle density to pixel density
- Vertex Clustering a good fit for this

MAXIS

Problem Solved?

MAXIS

Problem Not Solved

- Position-based meshes only!
- No normal discontinuities
- Not textured
- Not animated
- No vertex-based material info
- Most game meshes feature **all** of the above

MAXIS

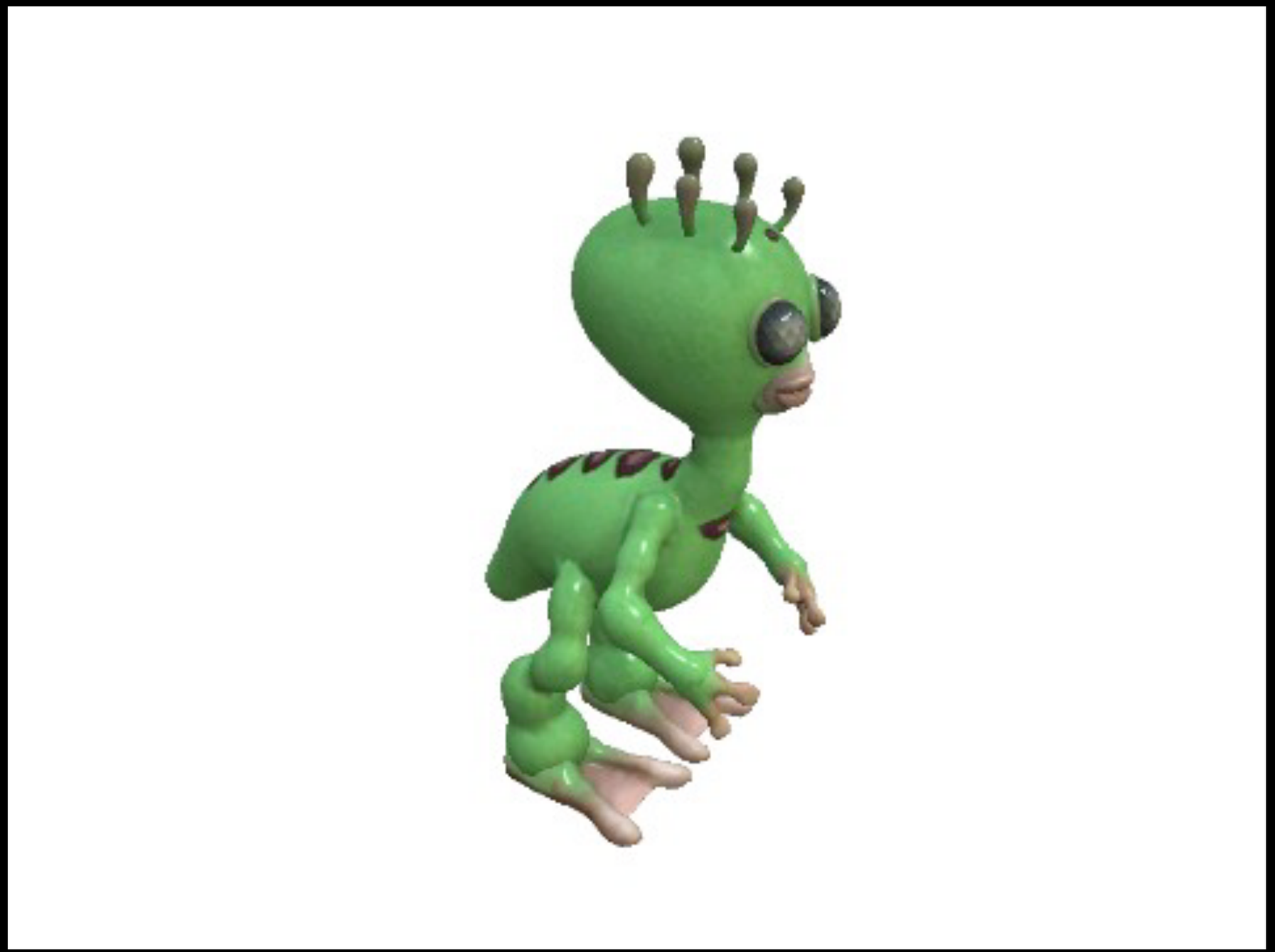
Attributes!

MAXIS

Animation!

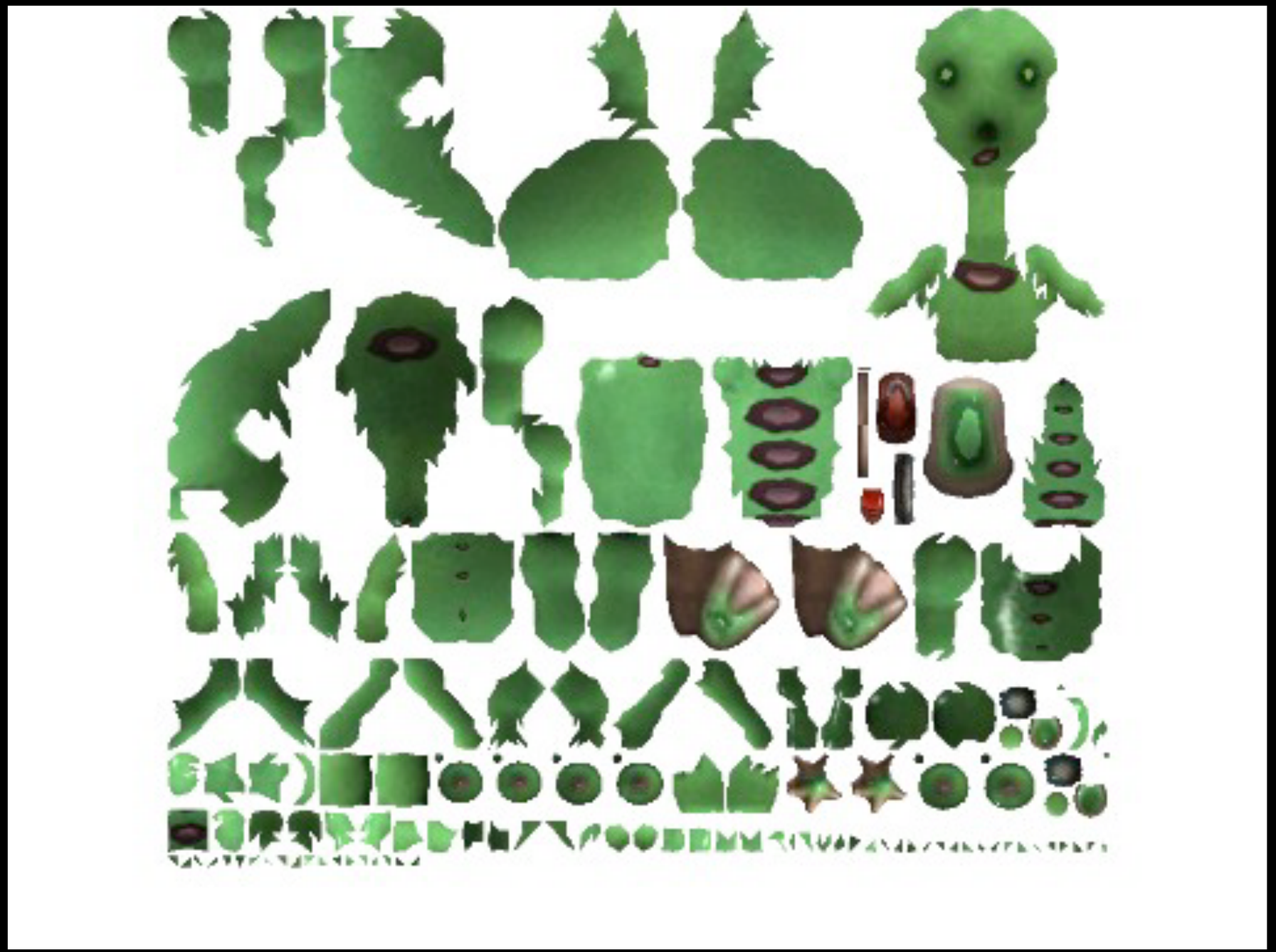
MAXIS

So what happens?



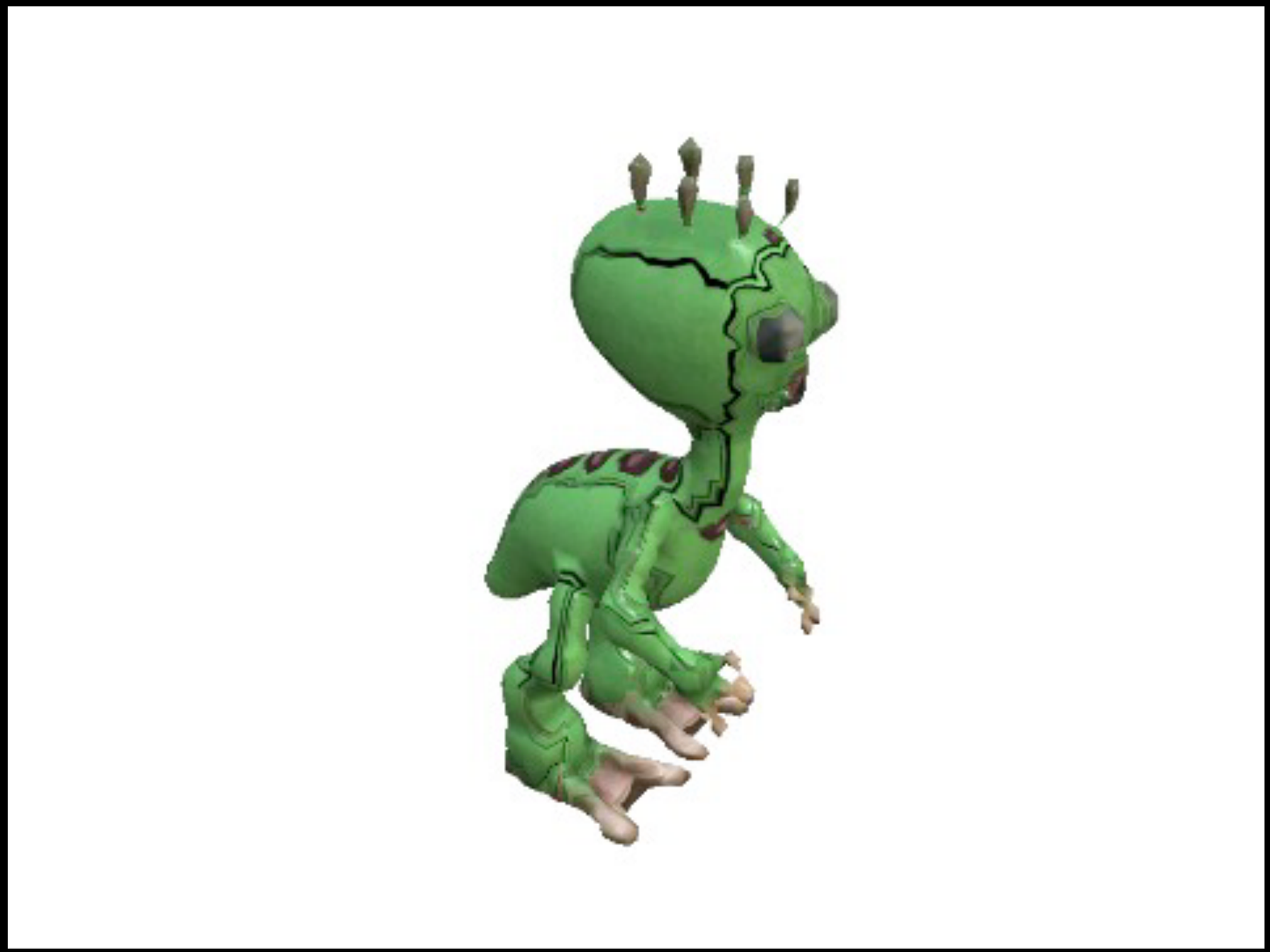
MAXIS

So what happens?



MAXIS

Stuff happens



MAXIS

UV Chart Mixing

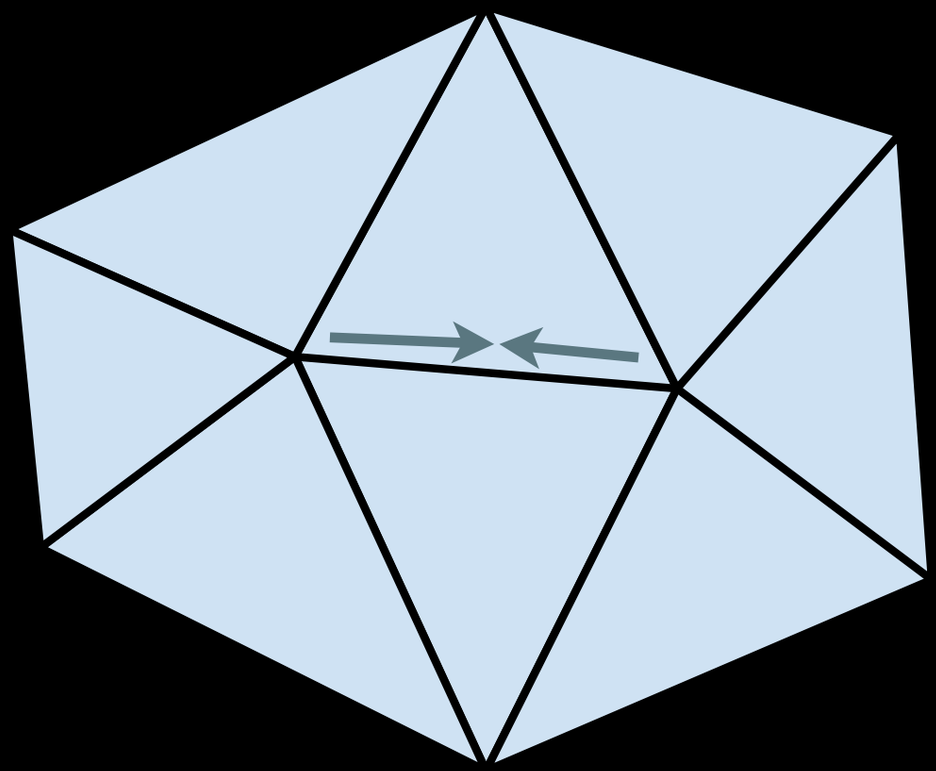
MAXIS

The Problem

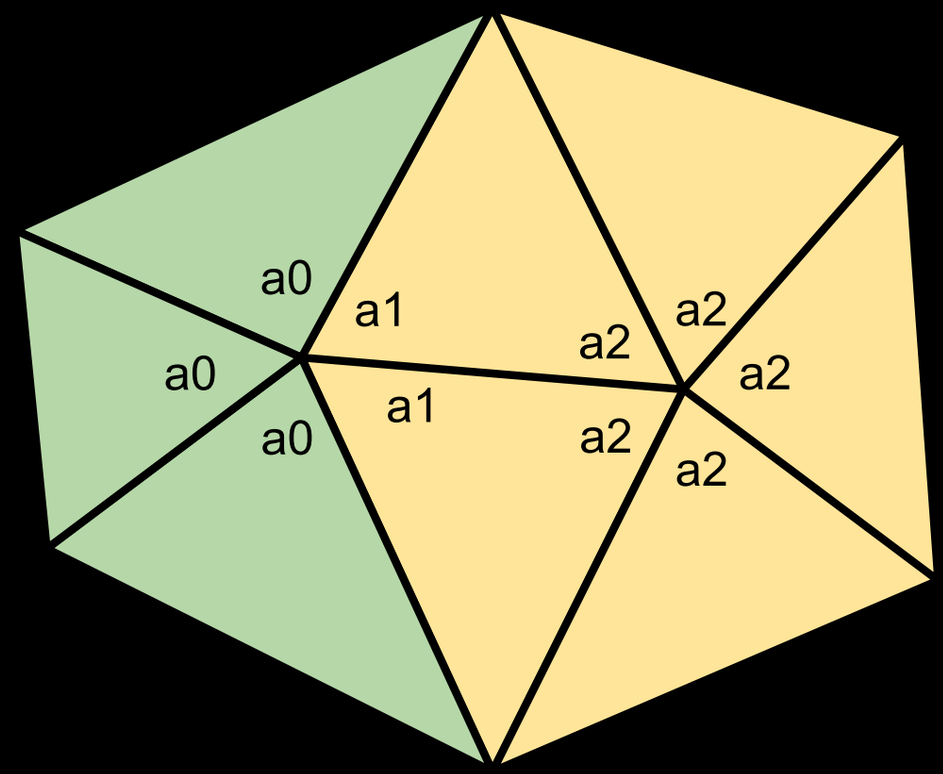
- Attributes have discontinuities
- UV charts particularly bad
- Also normal/material splits (see paper)
- Can’t just ignore!

MAXIS

Edge Collapse

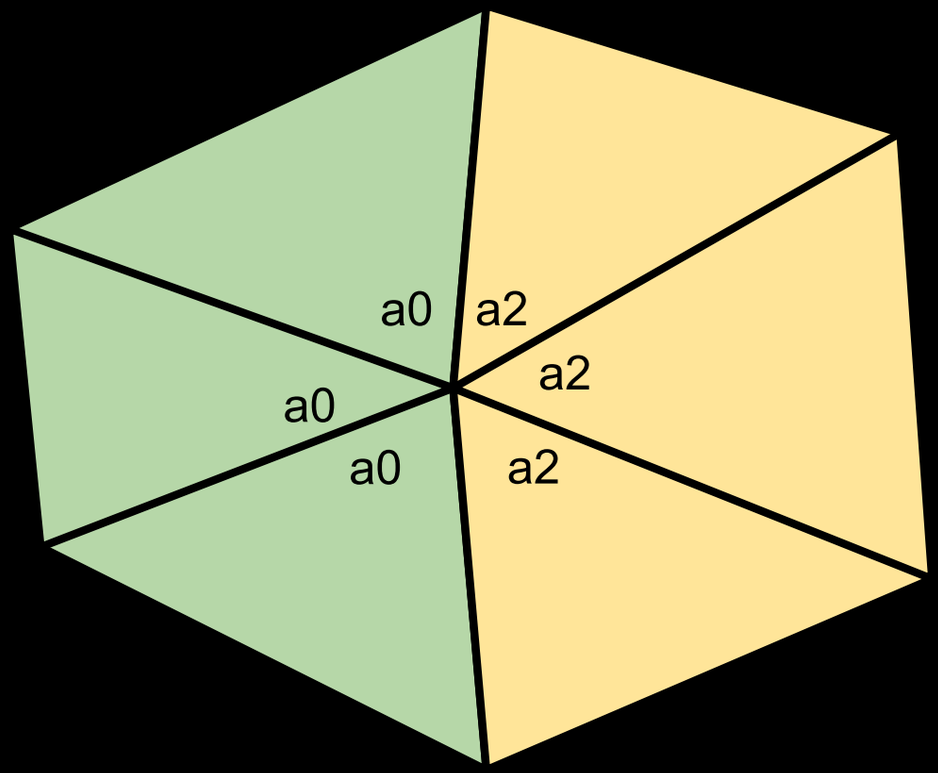


Edge Collapse Discontinuity



MAXIS

Discontinuity Preserved



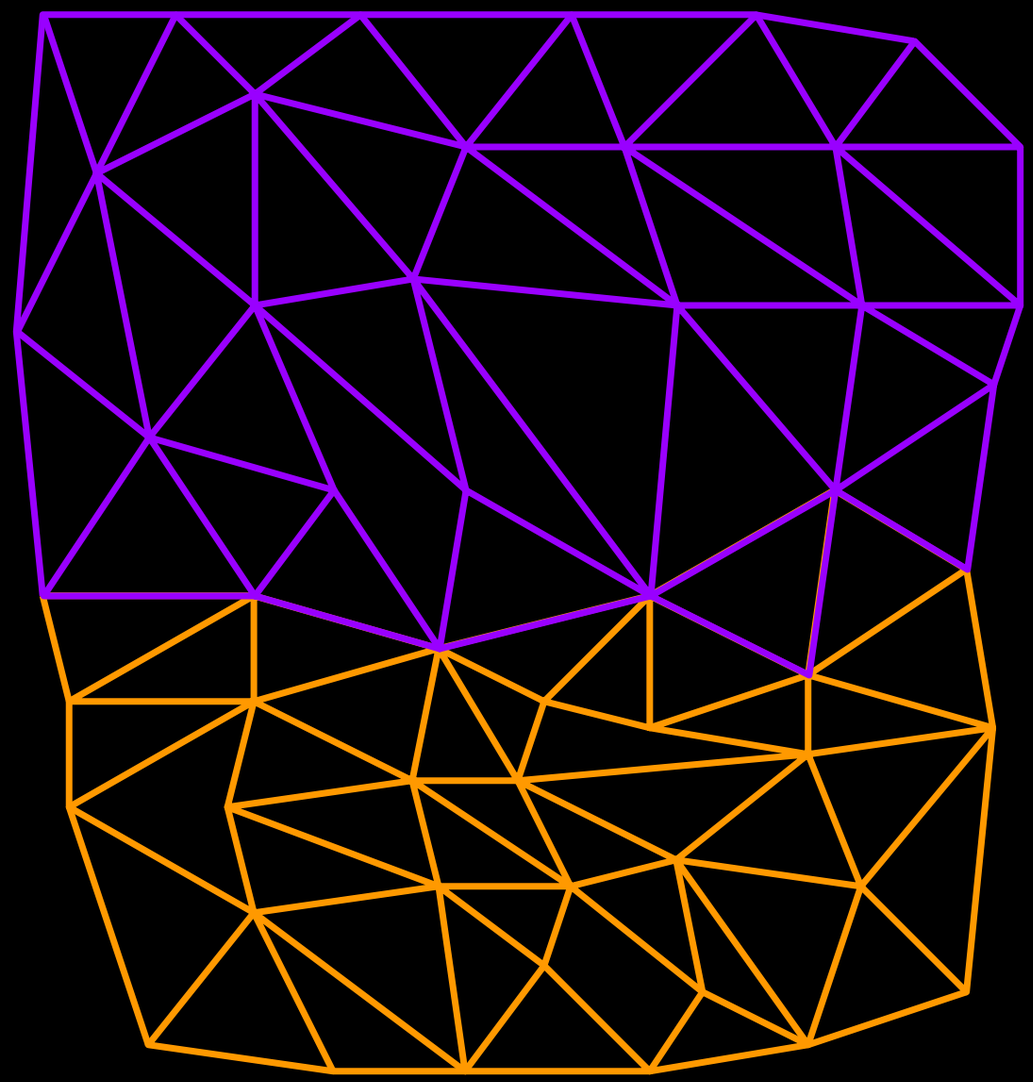
MAXIS

Edge Collapse

- Edge Collapse deals with attributes natively:
  - Discontinuities are preserved
    - Or removed when interior to the collapsed triangles
- Simplification is a series of discontinuity-preserving collapses

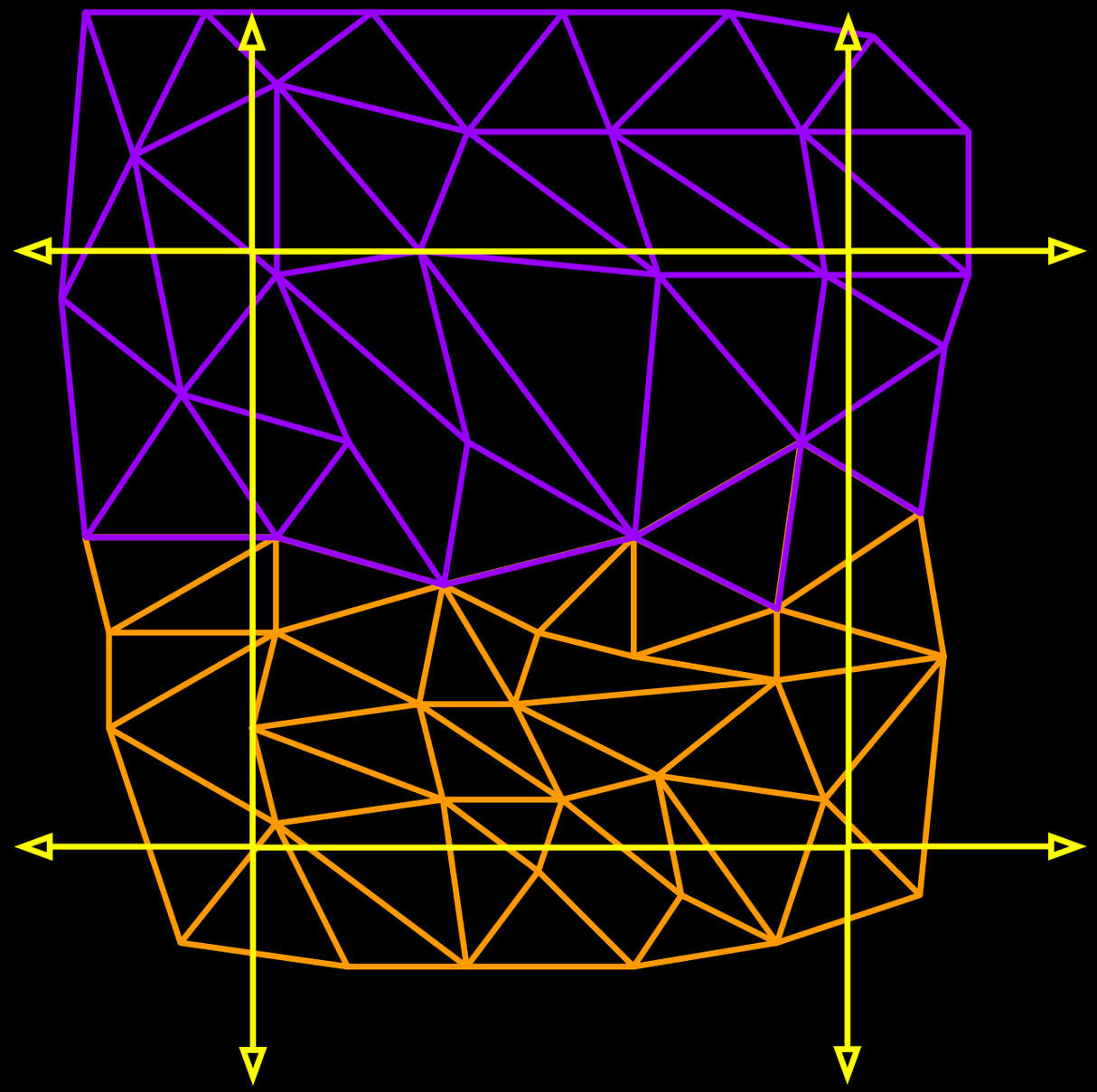
MAXIS

Vertex Clustering with Attributes



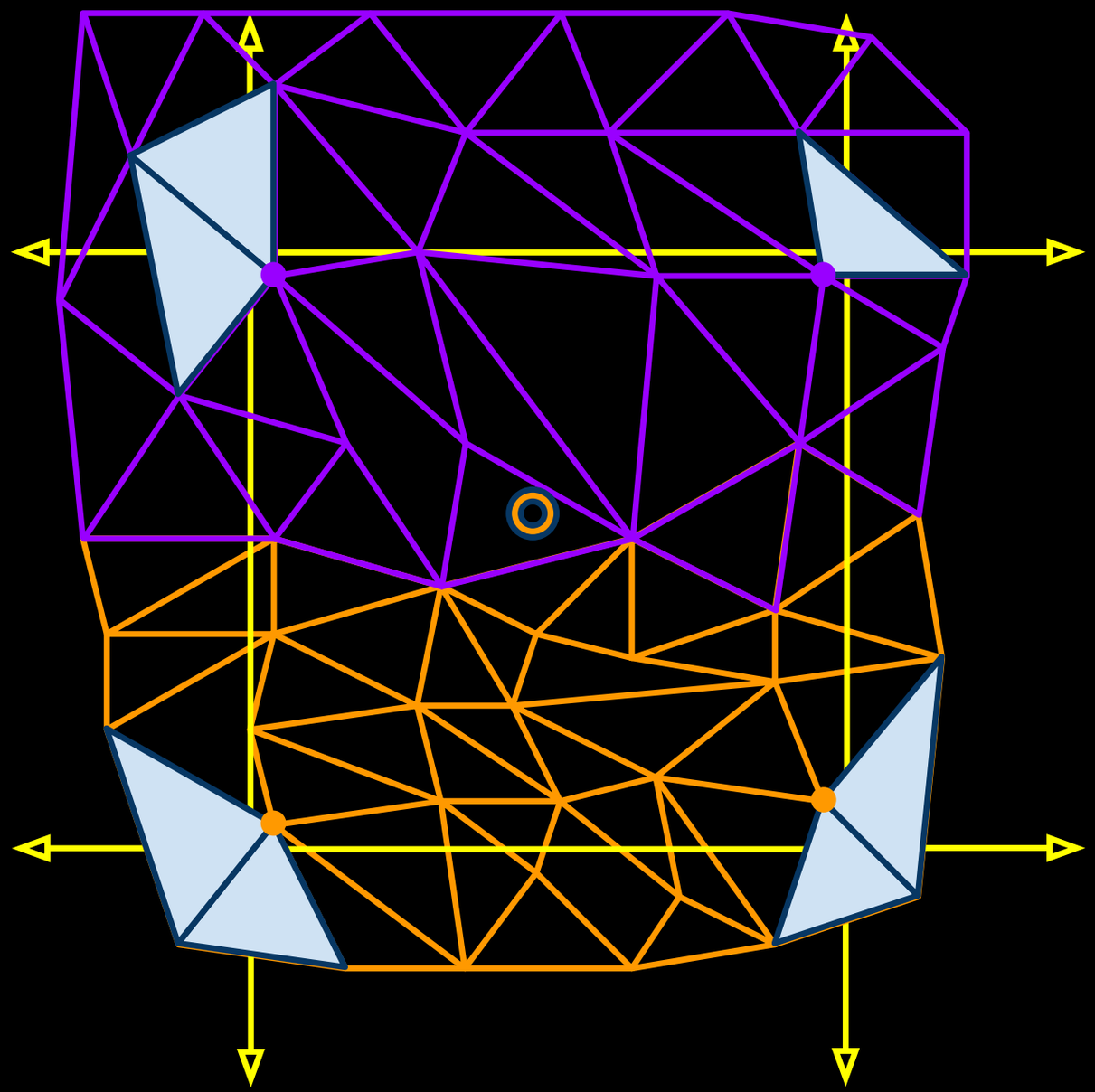
MAXIS

Vertex Clustering with Attributes



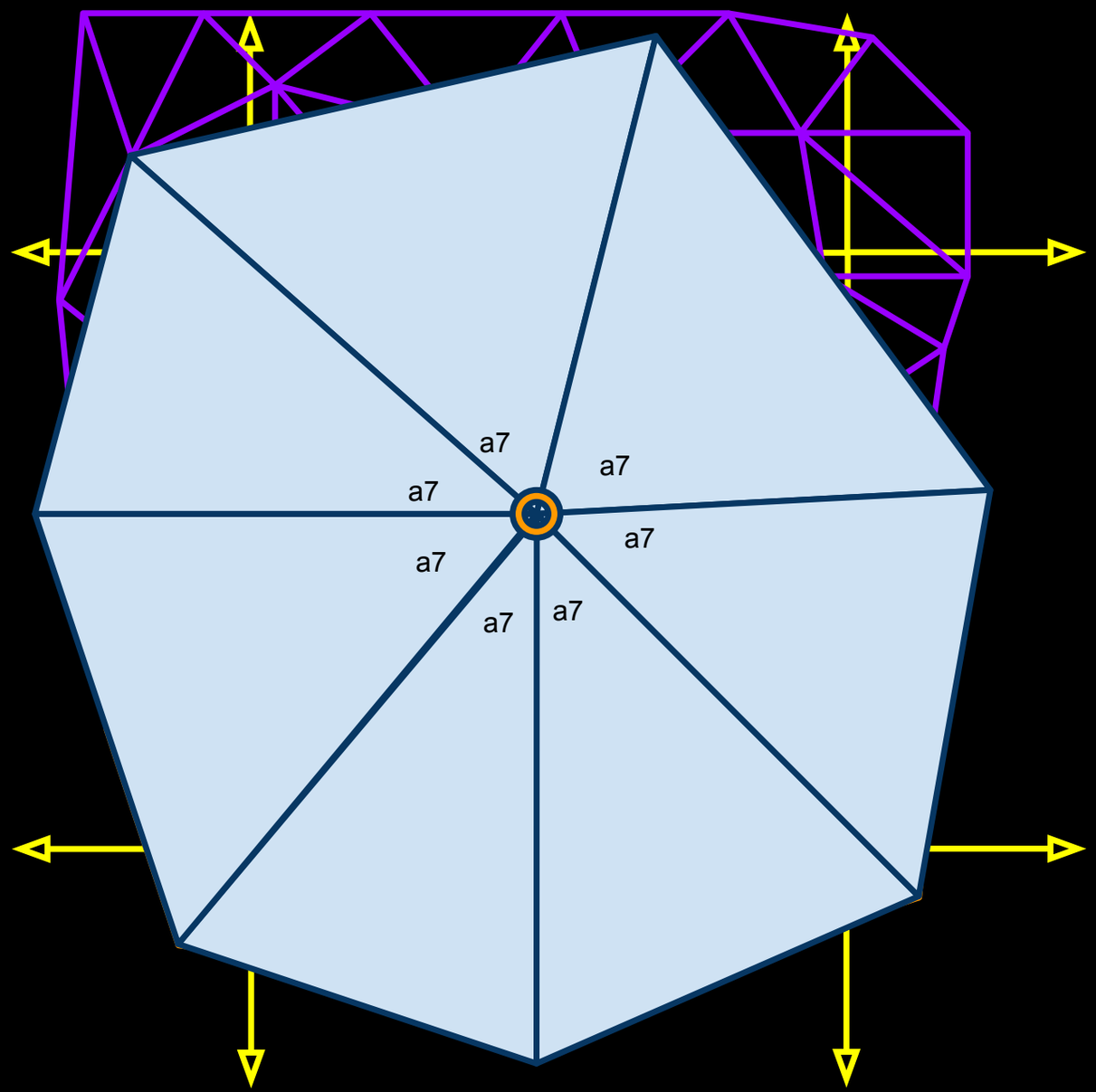
MAXIS

Vertex Clustering with Attributes



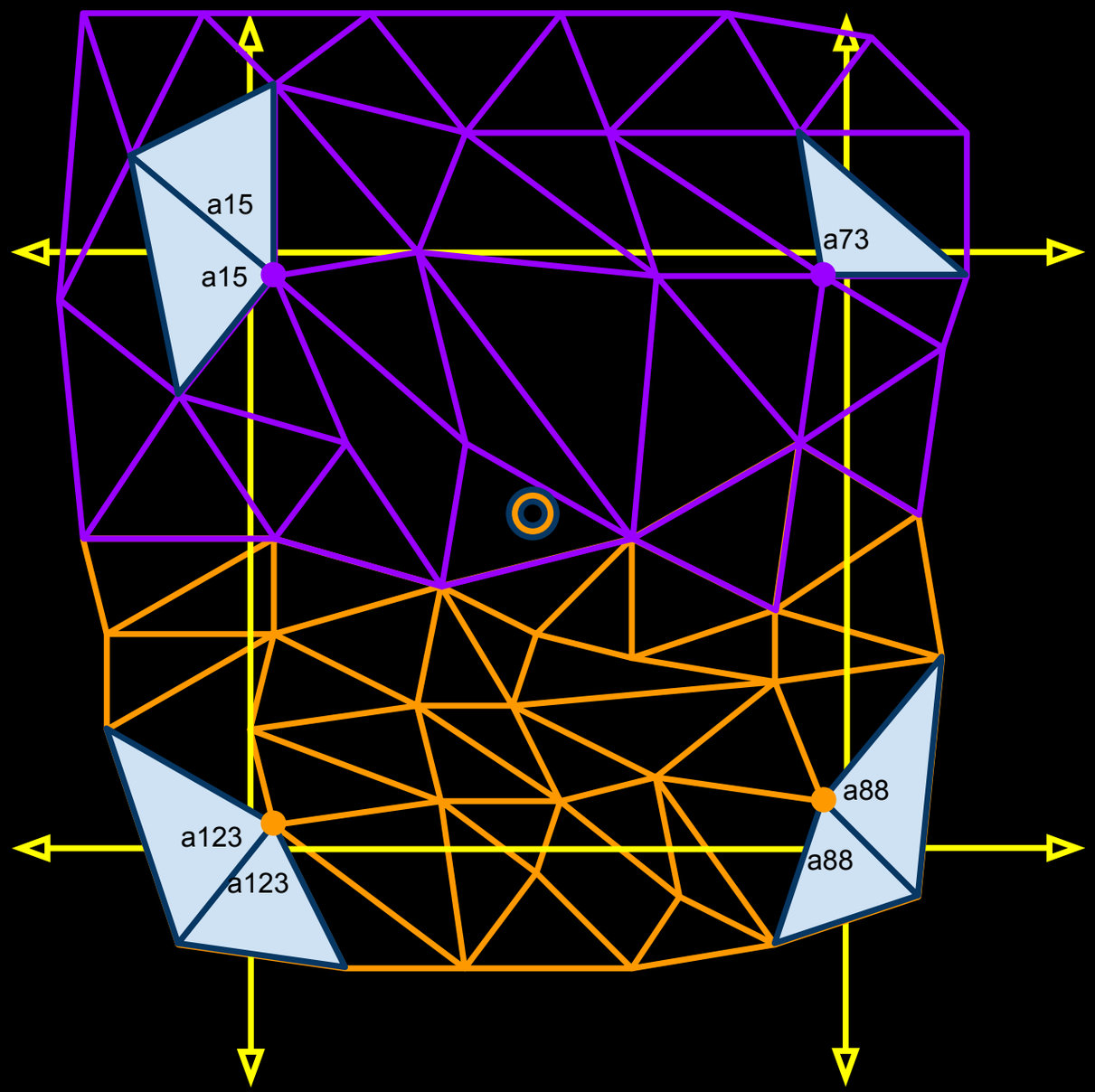
MAXIS

Oversharing



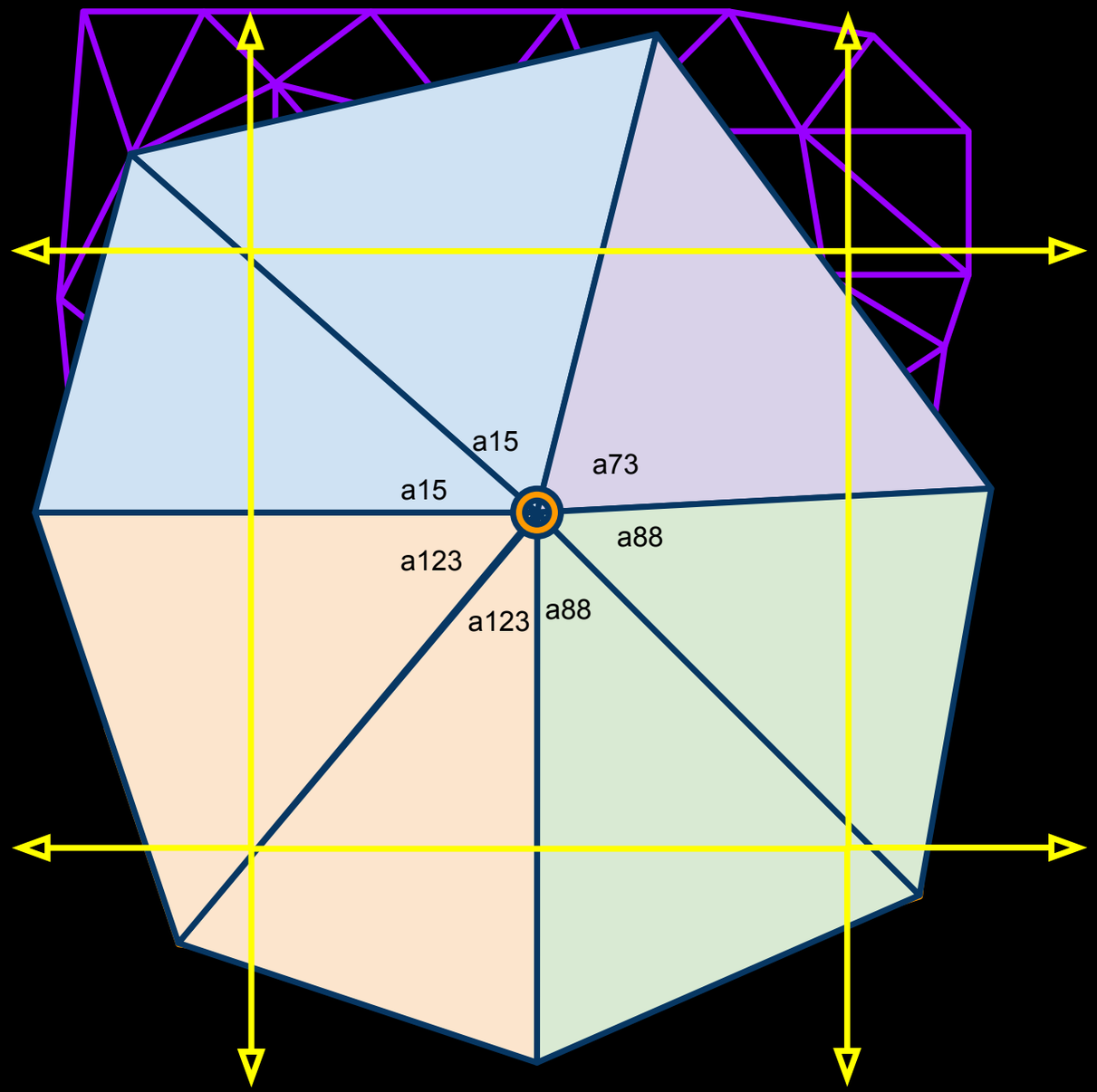
MAXIS

Input Attributes



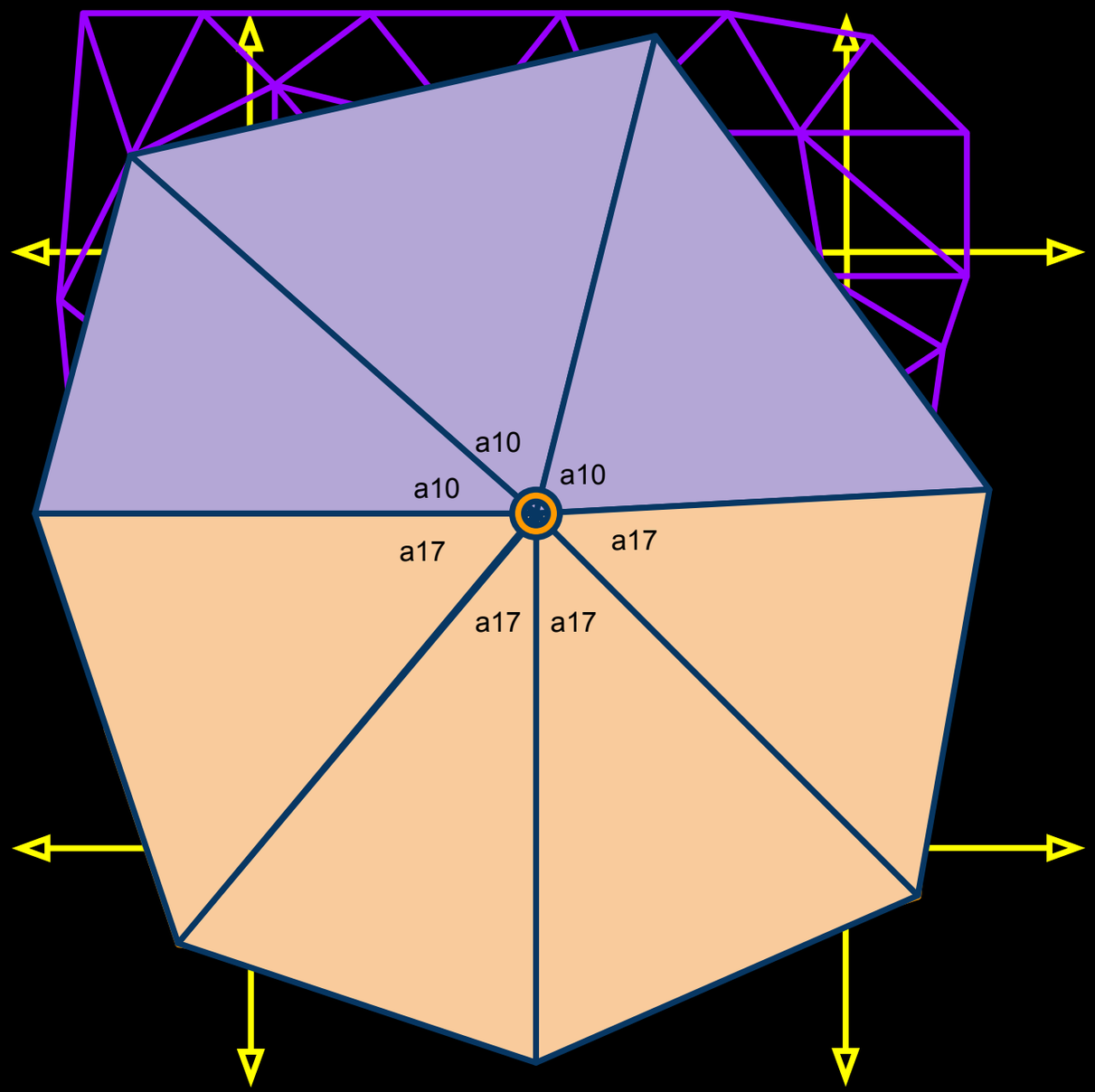
MAXIS

Undersharing



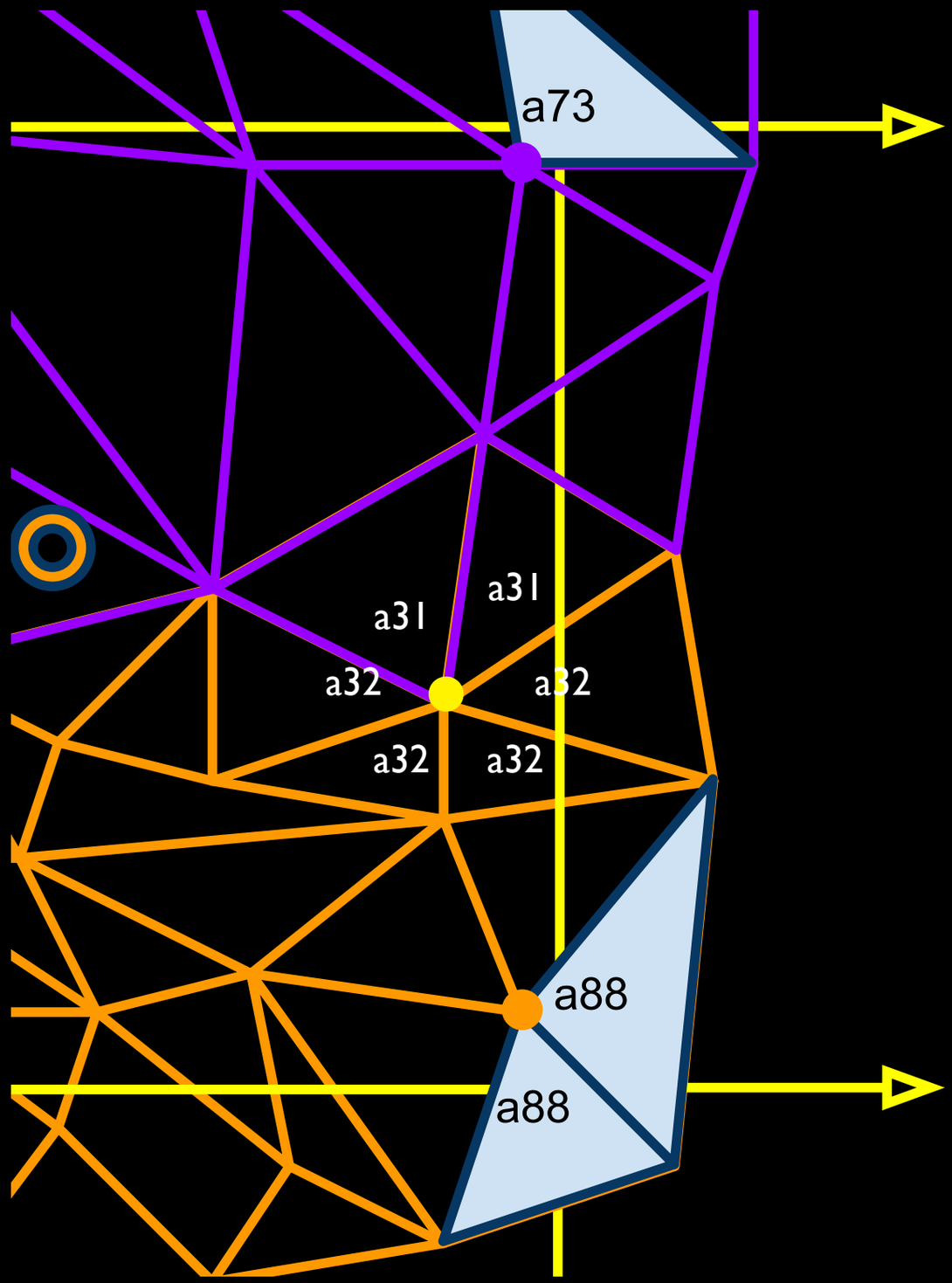
MAXIS

Just right



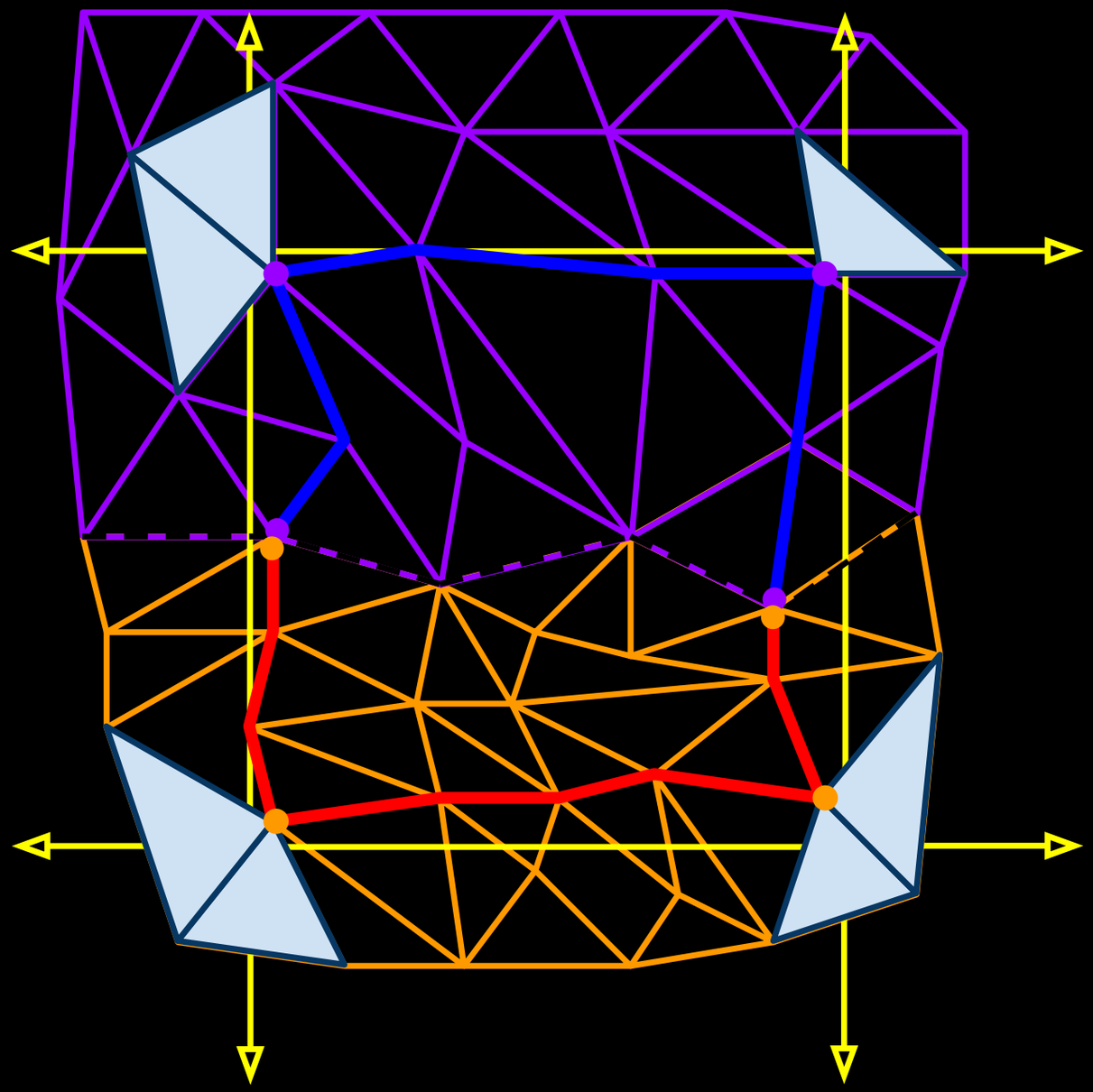
MAXIS

A Close-up



MAXIS

Insight: Boundary Edges



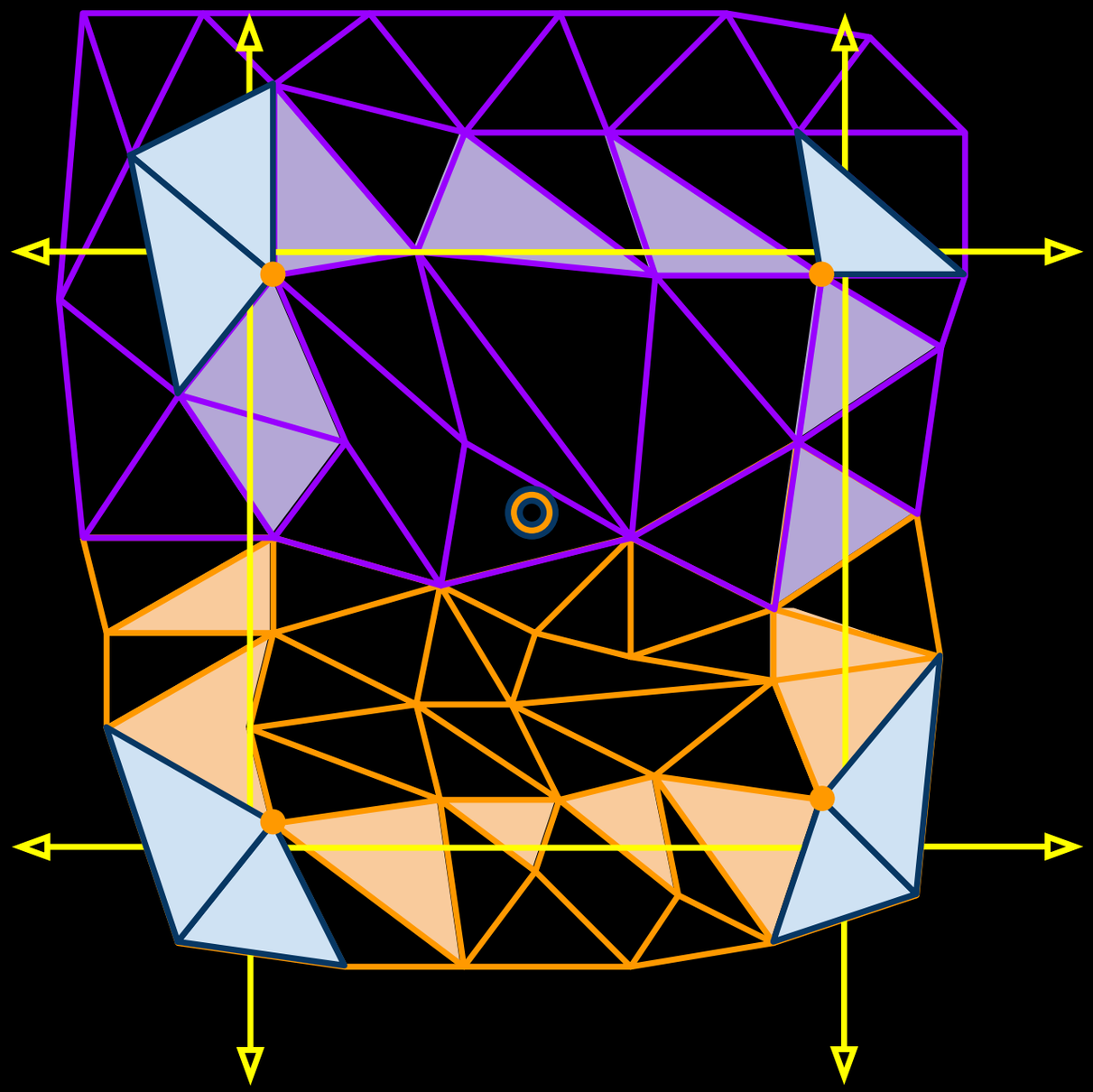
MAXIS

Issues

- How do we find the boundary edges?
- How do we use edges to link output vertices?
  - Without memory allocations
  - Efficiently

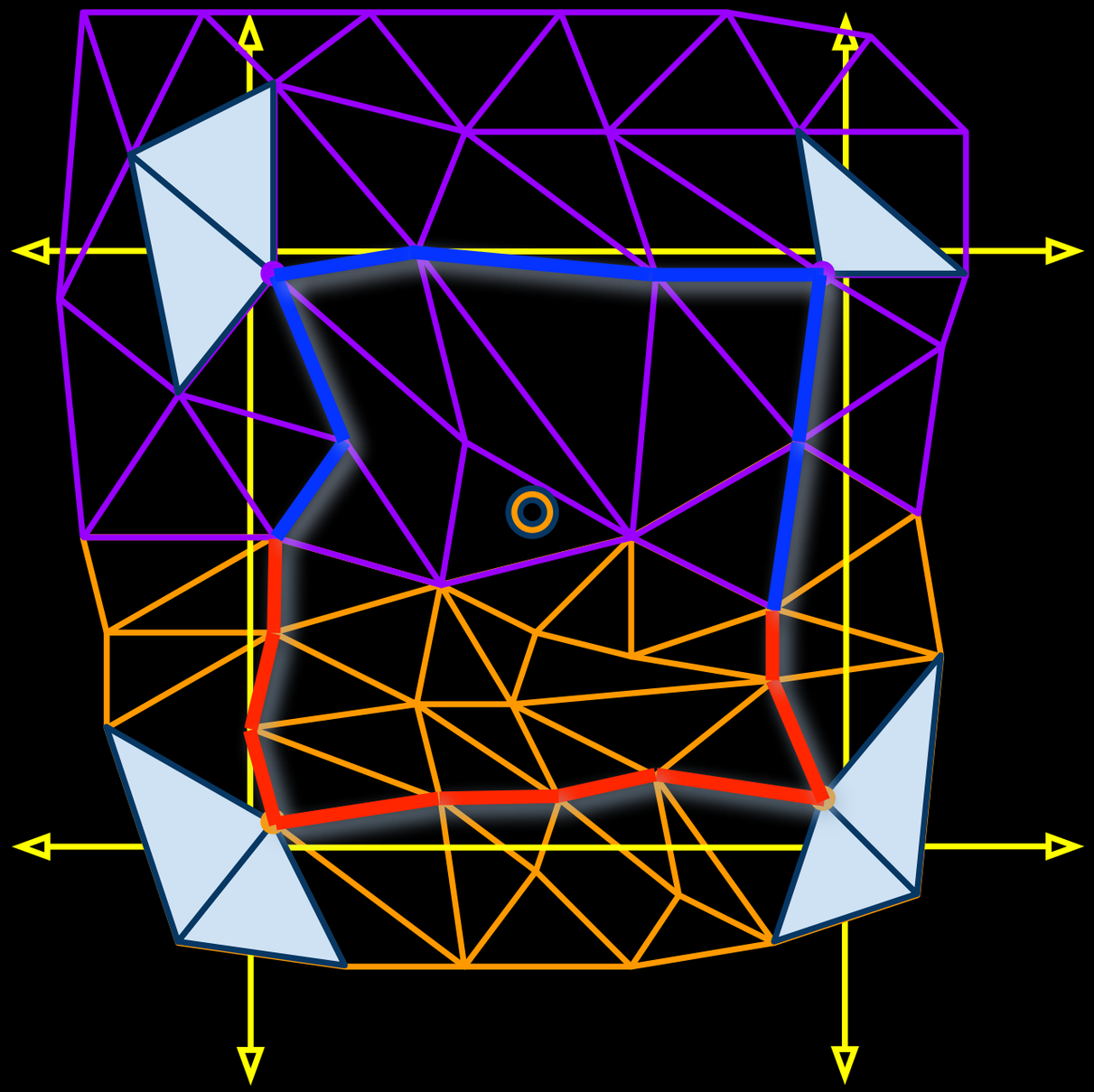
MAXIS

Finding Boundary Edges



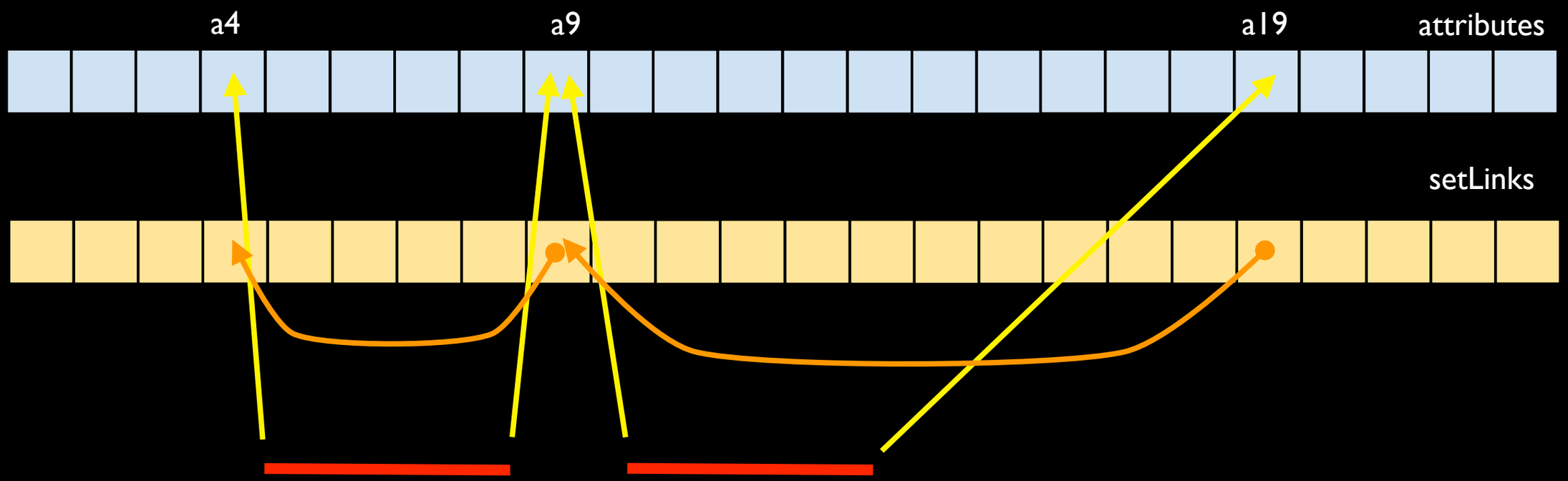
MAXIS

Boundary Edges



MAXIS

Boundary Edge Chains



MAXIS

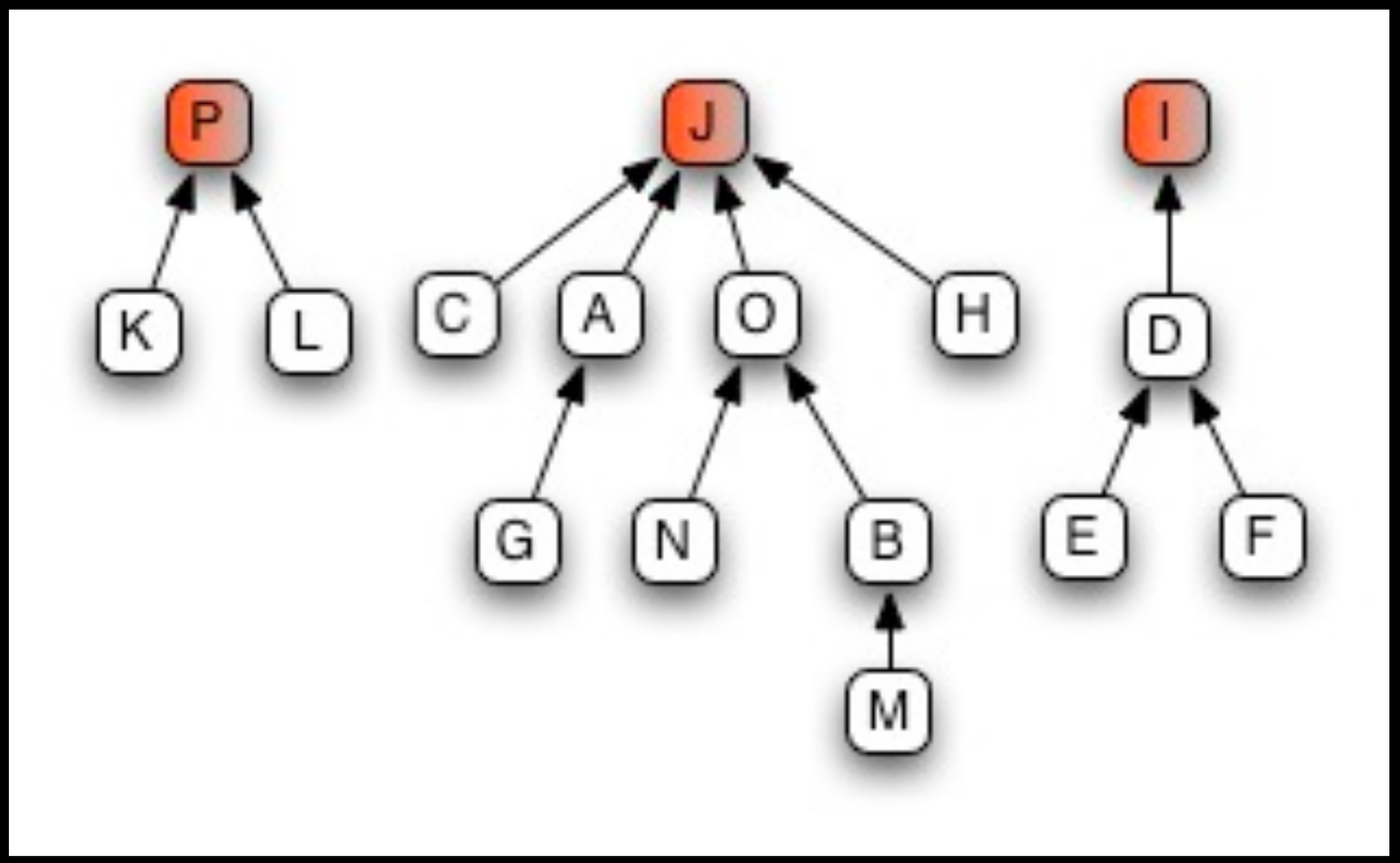
Grouping Edges

- Naive way
  - Treat as linked list
  - Insertion is O(k), k boundary edges
  - $O(k^2)$

- Observations
  - Insert k edges, query m edges, m << k

MAXIS

Union Find!



- Amortised O(1) insertion and query
- setLinks stores back pointers

MAXIS

Partial Path Compression

- Don’t do full path compression
  - Doesn’t help! In fact hurts
  - Extra memory accesses not paid for by results
- Do compress input vertices
  - Memory we have to access anyway.
  - Does result in minor gains

MAXIS

Building the sets

```
rv0 = dv0 = ea_n[ev[e0]]
rv1 = dv1 = ea_n[ev[e1]]
level = 0

while (setLinks[rv0]) >= 0)
    rv0 = setLinks[rv0]
    level++

while (setLinks[rv1] >= 0)
    rv1 = setLinks[rv1]
    level--

if (rv0 != rv1)
    if (level < 0)
        setLinks[rv0] = rv1
        setLinks[dv0] = rv1
    else
        setLinks[rv1] = rv0
        setLinks[dv1] = rv0
```

MAXIS

Using the sets

```
foreach (iv in 3 Nf)
    i  = ev[iv]
    dv = ea_n[i]
    rv = dv

    while (setLinks[rv] >= 0)
        rv = setLinks[rv]

    if (setLinks[rv] == -1)
        setLinks[rv] = -2 - dv;

    if (dv != rv)
        ea_n[i] = -2 - next
        setLinks[dv] = next
```

MAXIS

Results

Results

- Done!

- But can do more to improve Vertex Clustering quality

MAXIS

Shape Preservation

- A consequence of vertex clustering:
  - Any feature smaller than the cell size in at least one dimension will disappear completely

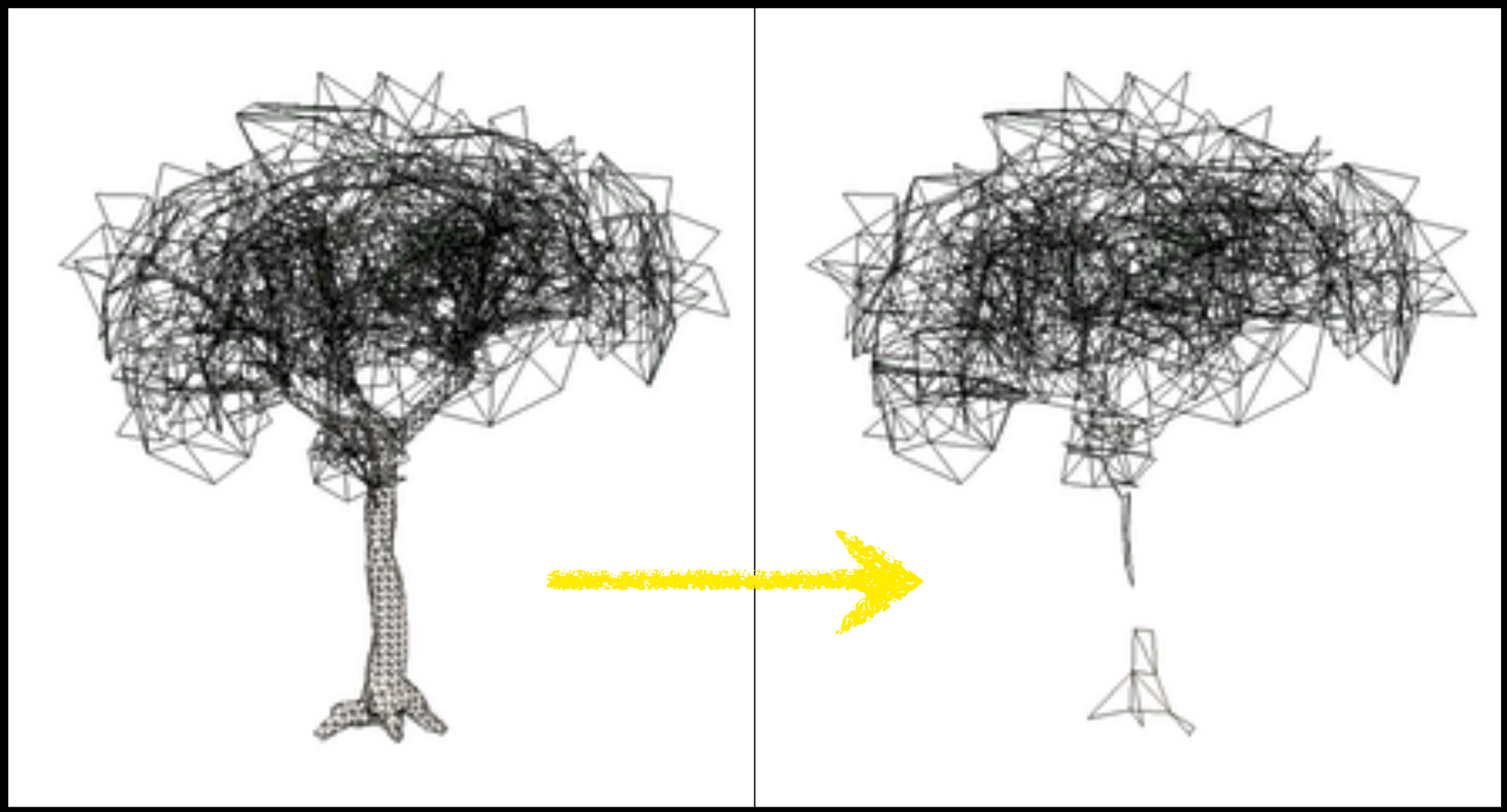
- Not always desirable!
  - Limbs
  - Poles, fences

MAXIS

Disappearing Trunk

MAXIS

Disappearing Trunk



MAXIS

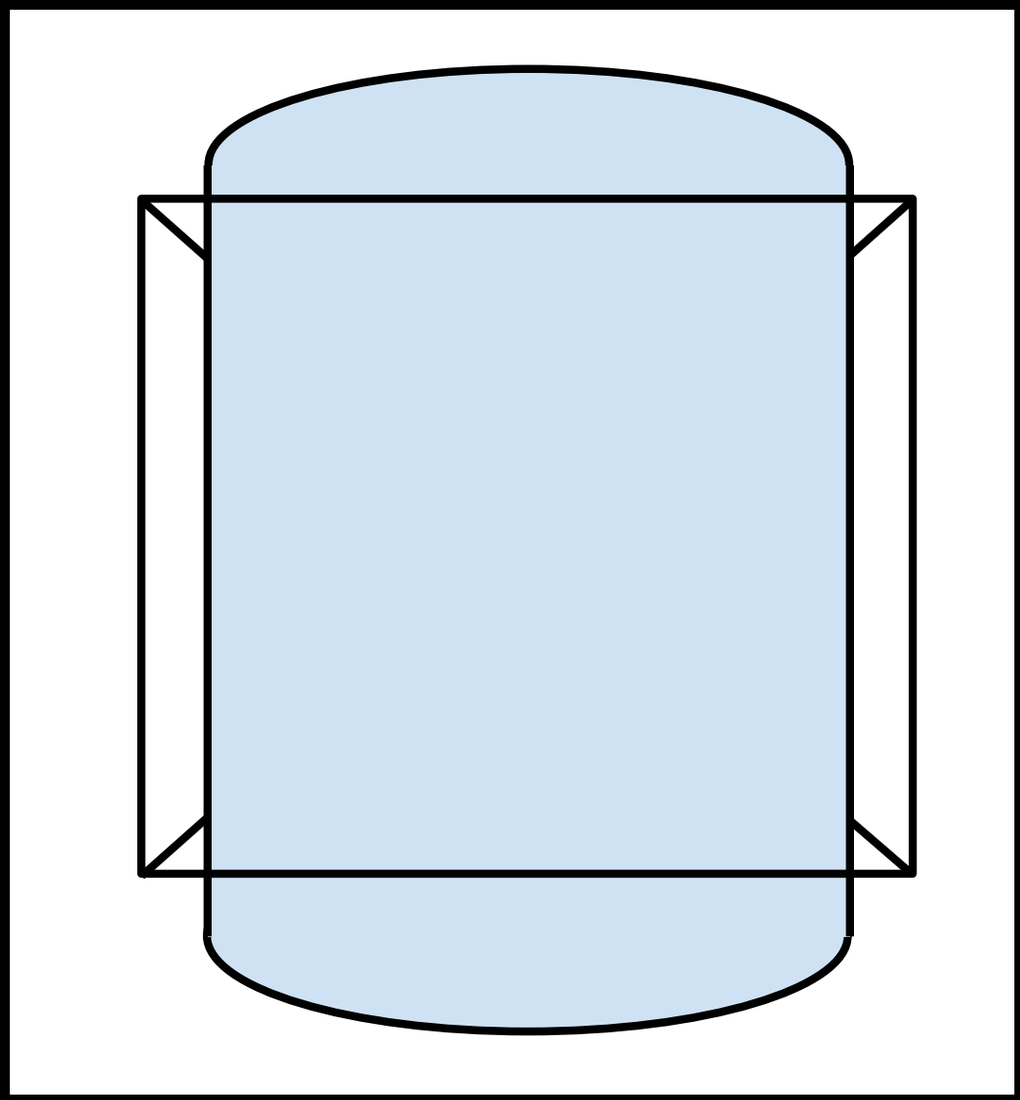
Shape Preservation

MAXIS

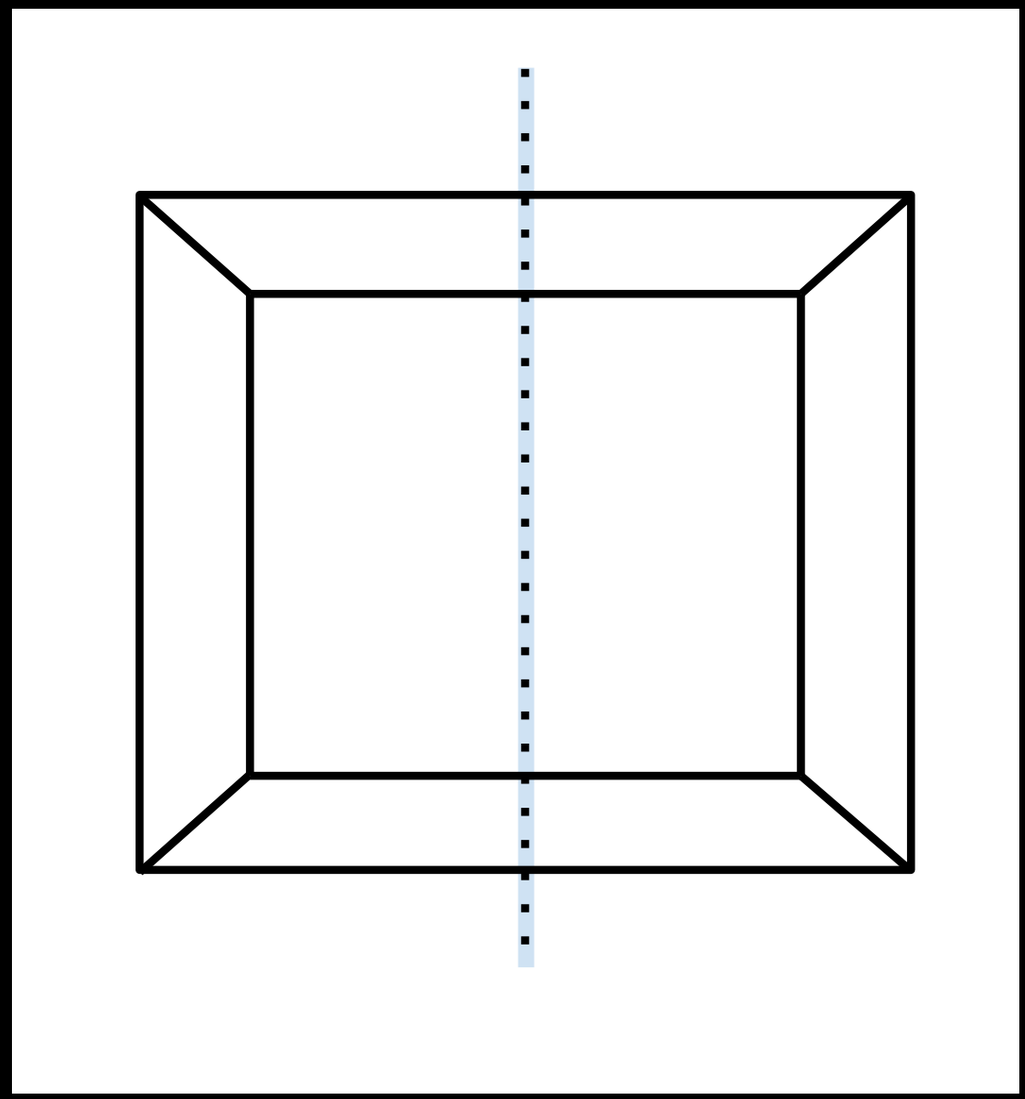
Shape Preservation

MAXIS

Thin Features

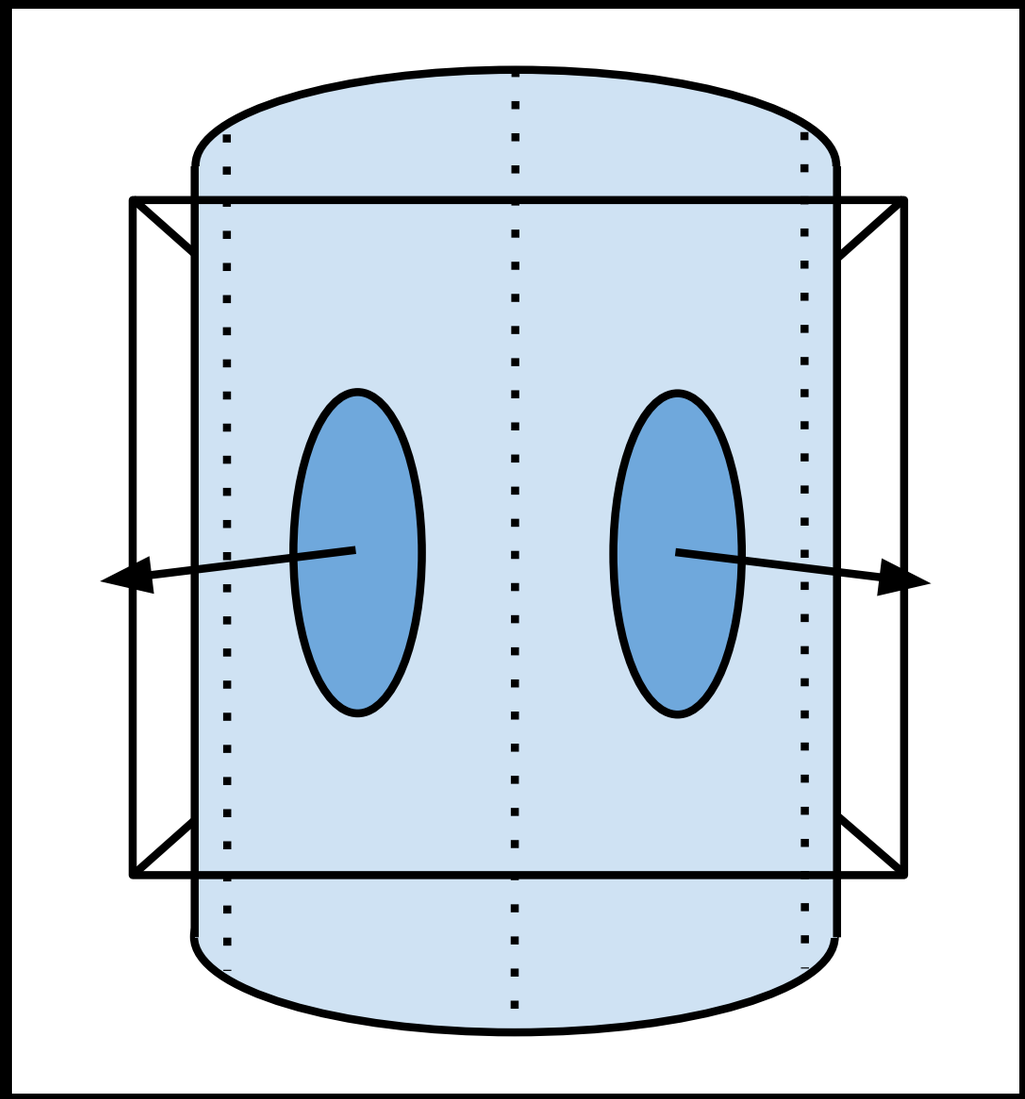


After Collapse



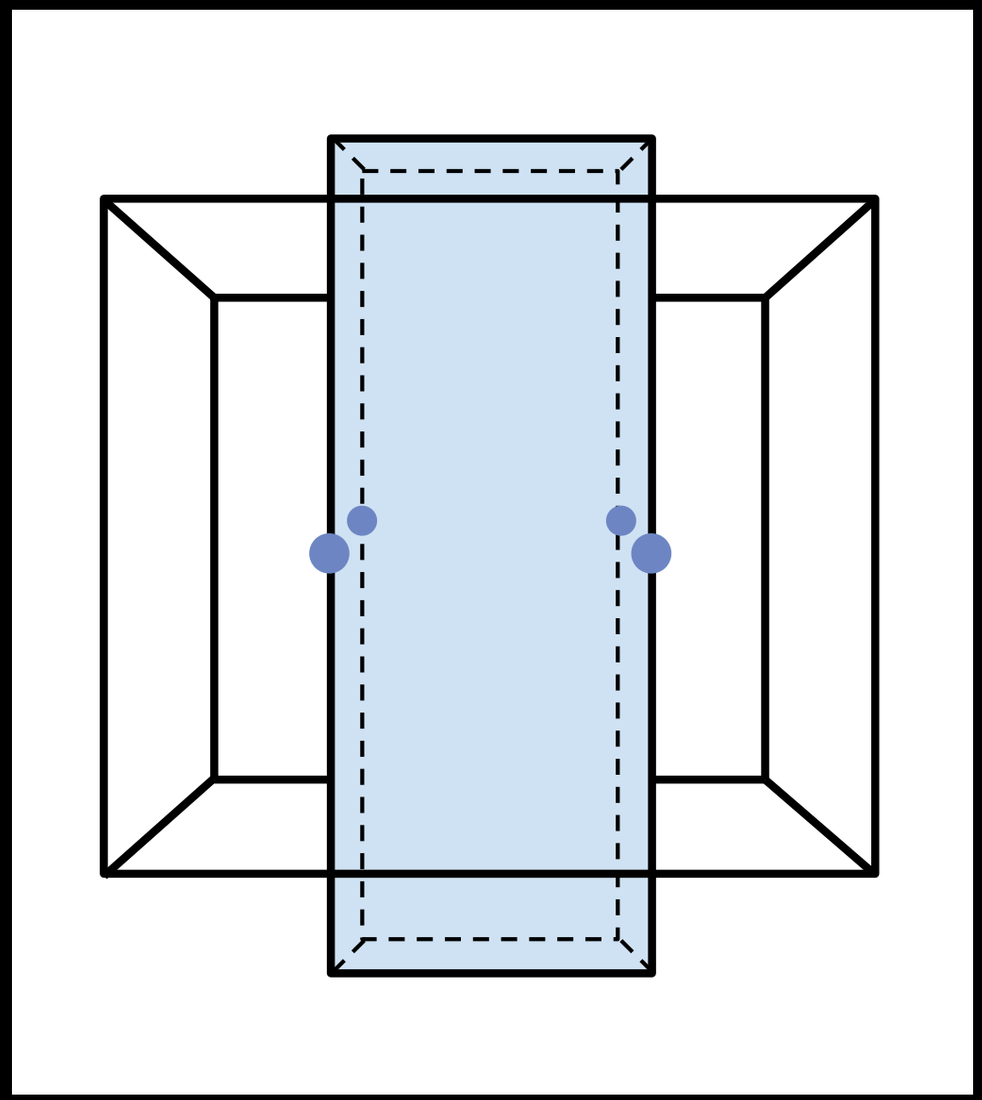
MAXIS

Insight: Normal Clustering

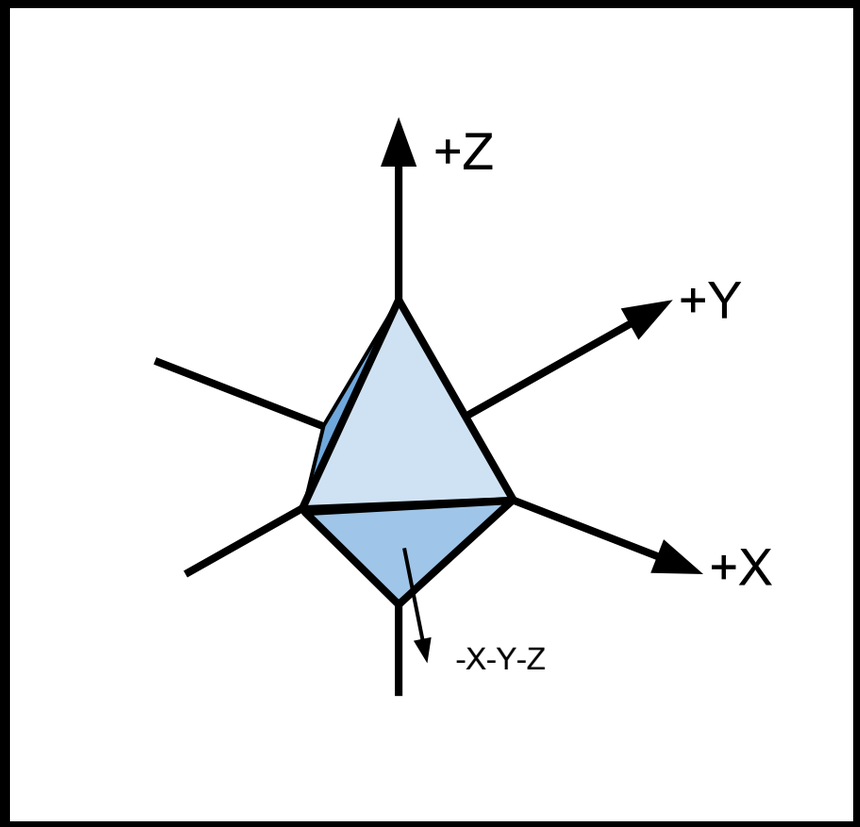


MAXIS

After Collapse



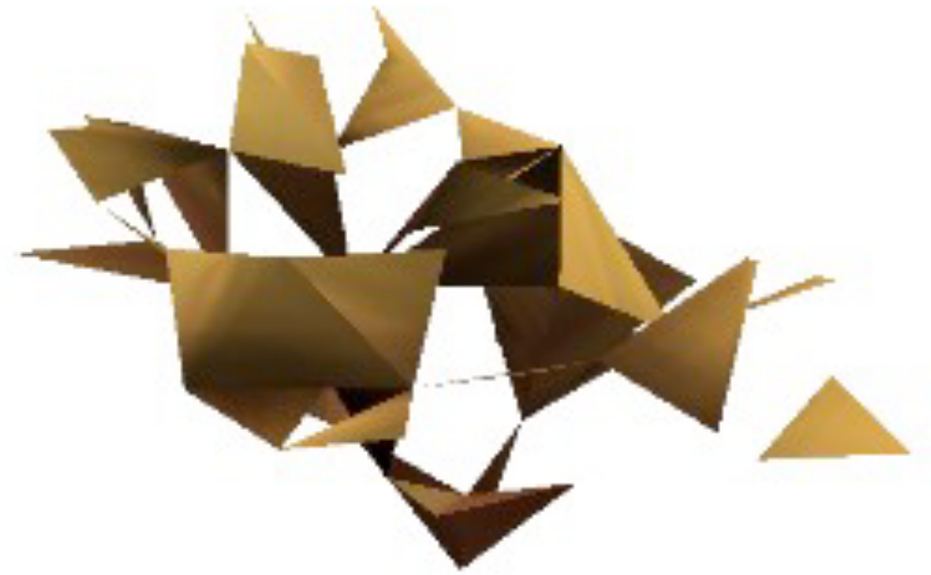
Cluster Strategy



- Quantize normal 8 ways
  - Trivial: assemble x/y/z sign bits
  - Cell label now `<cell>_<qnorm>`

MAXIS

Shape Preservation

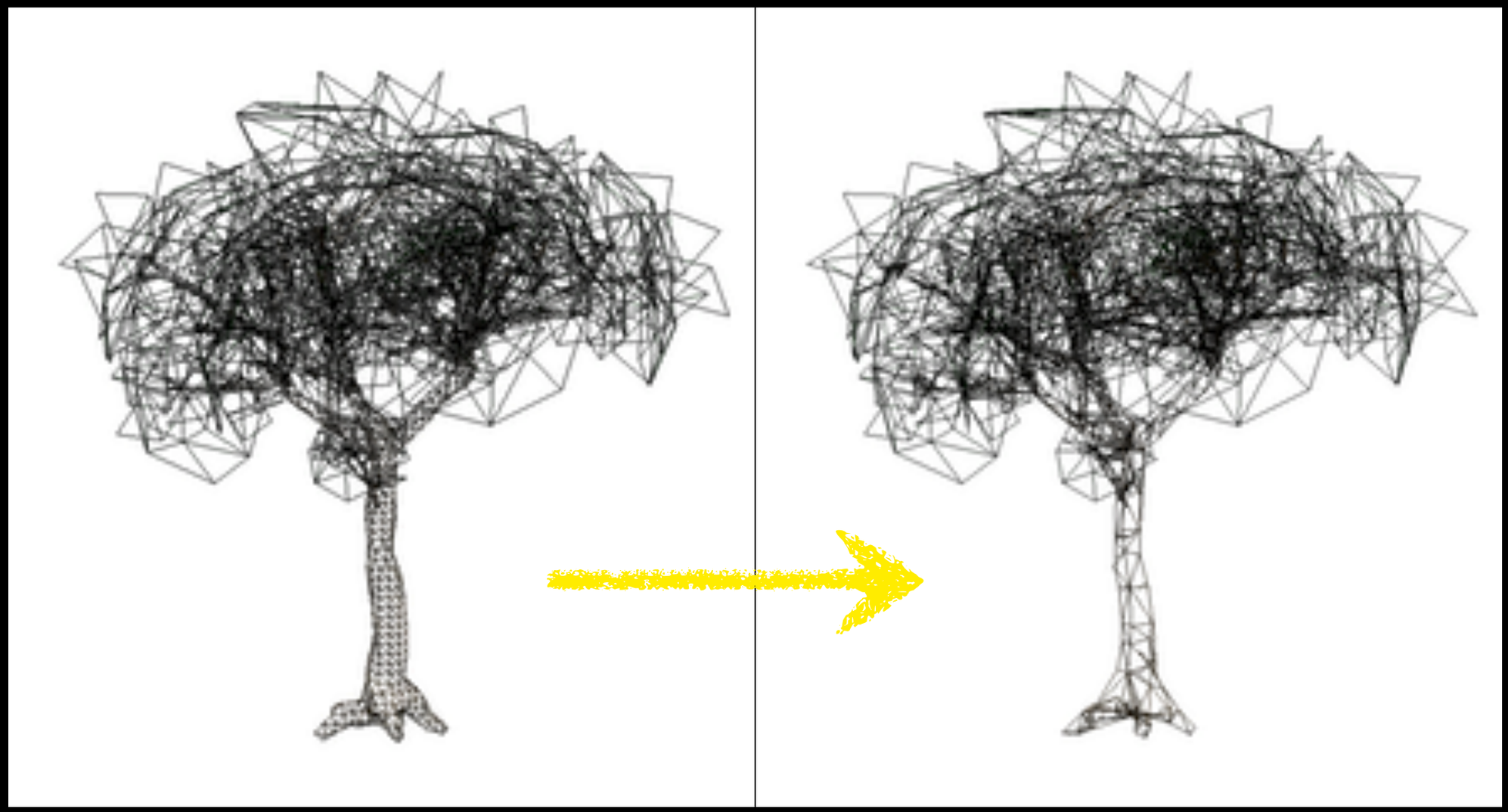


MAXIS

Trunks Preserved

MAXIS

Trunks Preserved



MAXIS

Bone Preservation

- Simplifying animated models leads to problems
  - Base pose is not representative of all animated poses
  - May collapse parts of the mesh together that are animated independently

MAXIS

Webbing

Fixing Unwanted Collapses

- Use same approach as normal clustering
- Append major bone index to the vertex label
  - Prevents any triangle spanning two bones from being removed
  - Avoids cross-limb collapses
  - Label: `<cell>_<qnorm>_<bone>`
- Fast to look up with sorted weights

MAXIS

Result

Simplification Control

- Information from game can help:
  - Know which parts of the mesh are animated
  - Know which parts are detail and can be heavily simplified
  - Use to affect simplification factor (cell size) and what extensions to use
- See paper

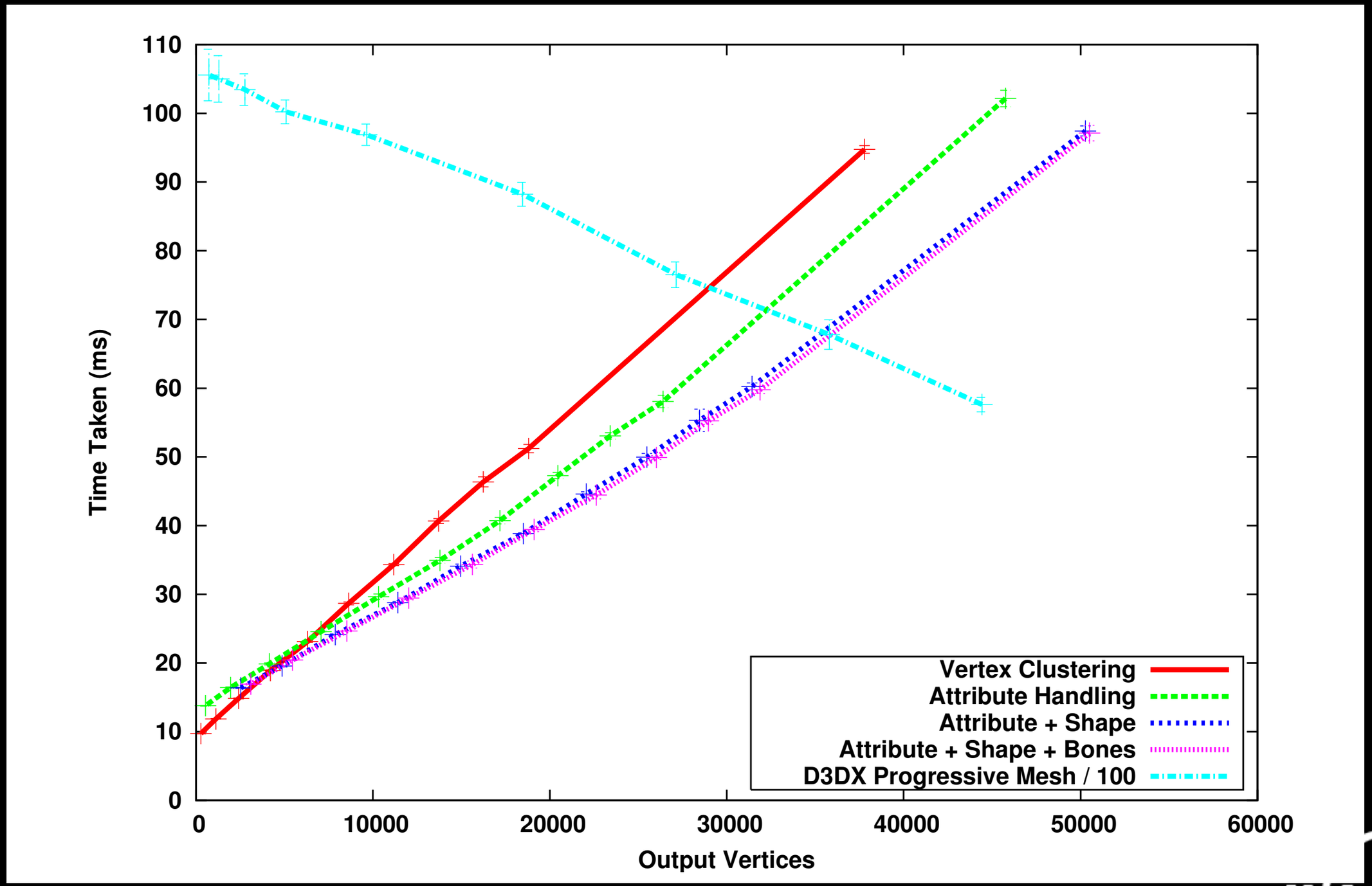
MAXIS

Label Size

- We've been merrily extending the vertex label, does that hurt us?
  - `<cell>_<qnorm>_<bone>_<tag>`
- Previously: xyz x 32 bits, hash to output index
- Now: 3 x 24 bits + normal (3 bits) + bone (8 bits) + tag (5 bits)
- No change to cluster index lookup!

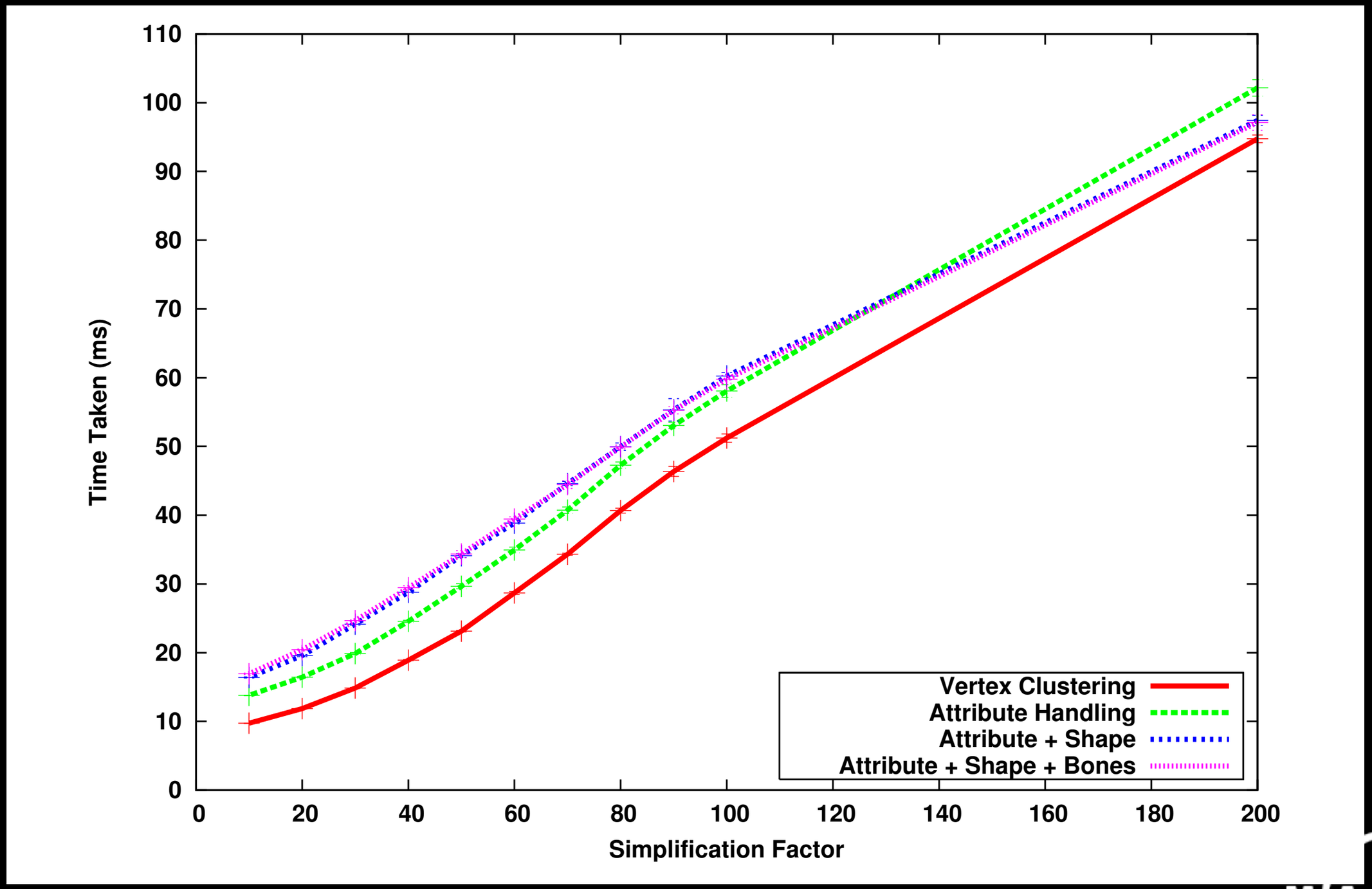
MAXIS

Results



MAXIS

Results



MAXIS

Summary

- Vertex Clustering adapted for production quality meshes
- High speed
  - Memory friendly, faster for lower LODs
  - Job-friendly, mostly Compute-friendly
- Robust!
  - No restrictions on input mesh

MAXIS

Testing!

- There are 160 million[1] player-created models published on http://www.spore.com/sporepedia

- Our system has generated 3-4 LODs for all of them with no issues.

[1] 165,568,111 @ 9am

MAXIS

Acknowledgements

- Ocean Quigley
- Maxis
  - Core Engine Team
- Lucy Bradshaw

- Questions?

MAXIS

Parallelism

- Label assignment is embarrassingly parallel
- Compaction of triangle list = stream compaction
- Boundary edges work at the cell level
- Ideally suited for SPU

MAXIS

Base VC

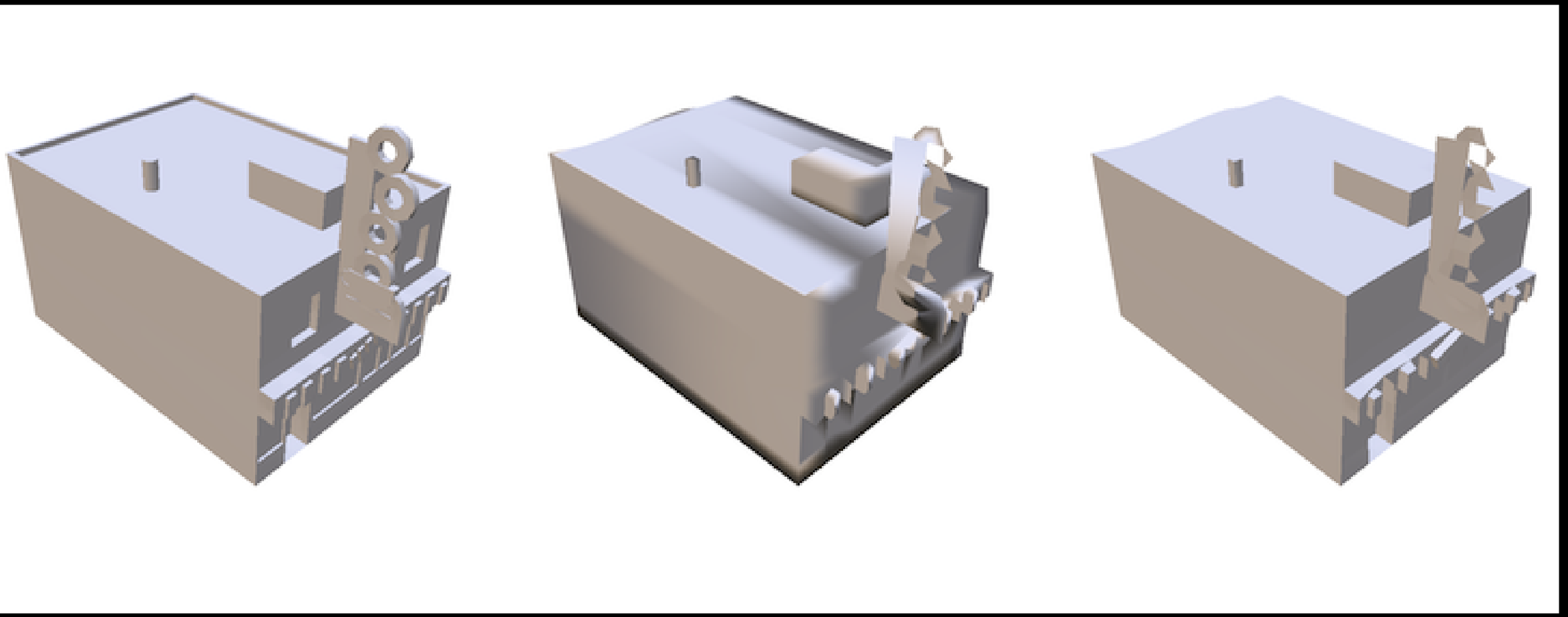
```
QuantiseVertices:
    foreach (i in Nv)
        Generate cell label
        Record replacement index ep[i]
        Accumulate p into representative point p_label

RemoveDegenerateTriangles:
    foreach (i in Nf)
        if (p[ep[ev[3i]]] = p[ep[ev[3i + 1]]] = p[ep[ev[3i + 2]]])
            Discard triangle

Compact:
    Share all vertices with identical element references
    Remove all unindexed data
```

MAXIS

Normal Discontinuities



MAXIS