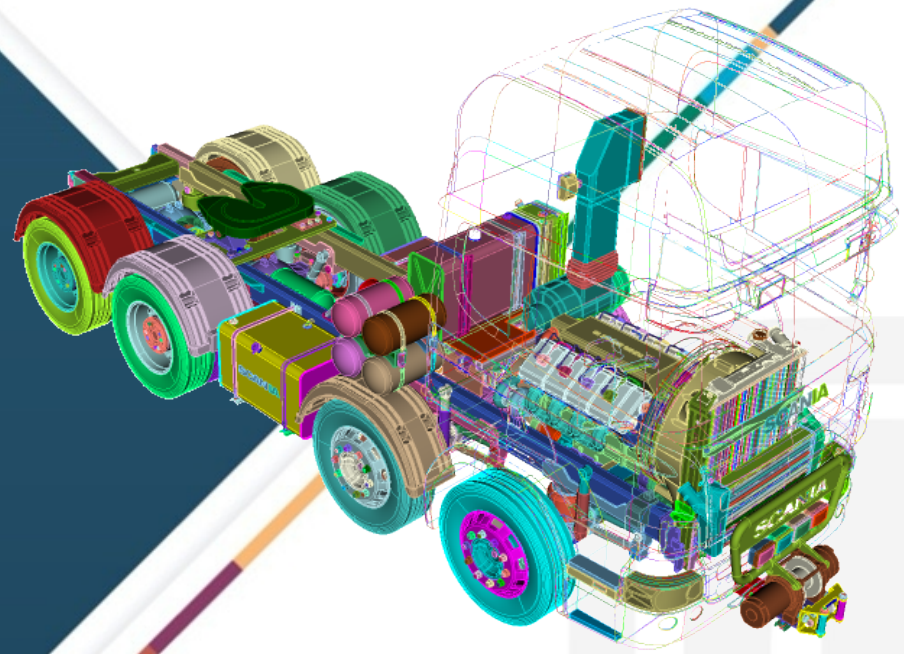
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2021-8928C

Sandia National Laboratories

Exceptional service in the national interest

Machine Learning Applications for Defeaturing and Model Preparation



Steven Owen, Corey Ernst,
Armida Carbajal, Matthew Peterson

July 25, 2021

16th US Congress on Computational Mechanics

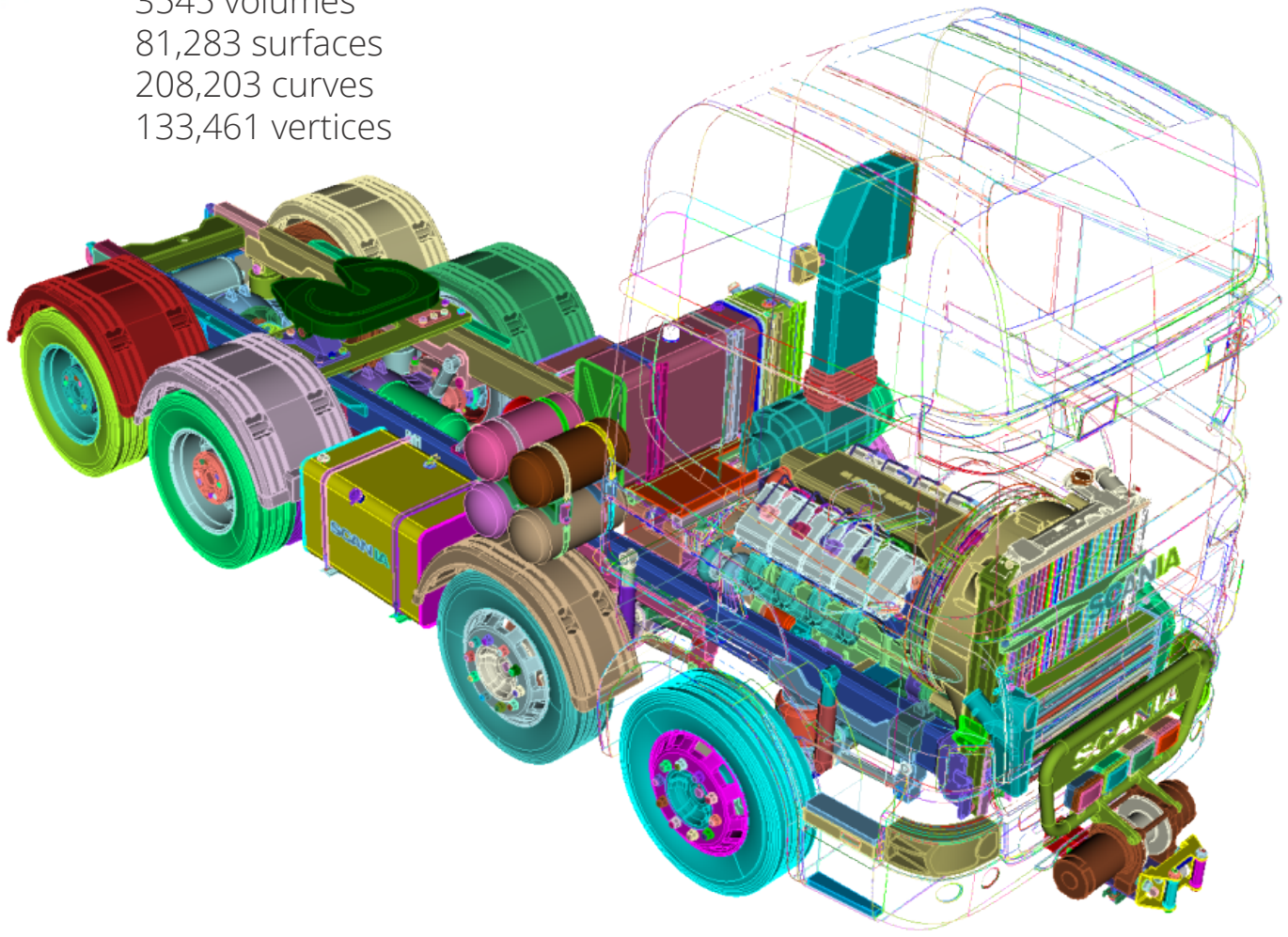
July 25-29, 2021
A Virtual Event

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Rapid CAD to Simulation with Machine Learning

Commercial Truck CAD Model
3545 volumes
81,283 surfaces
208,203 curves
133,461 vertices

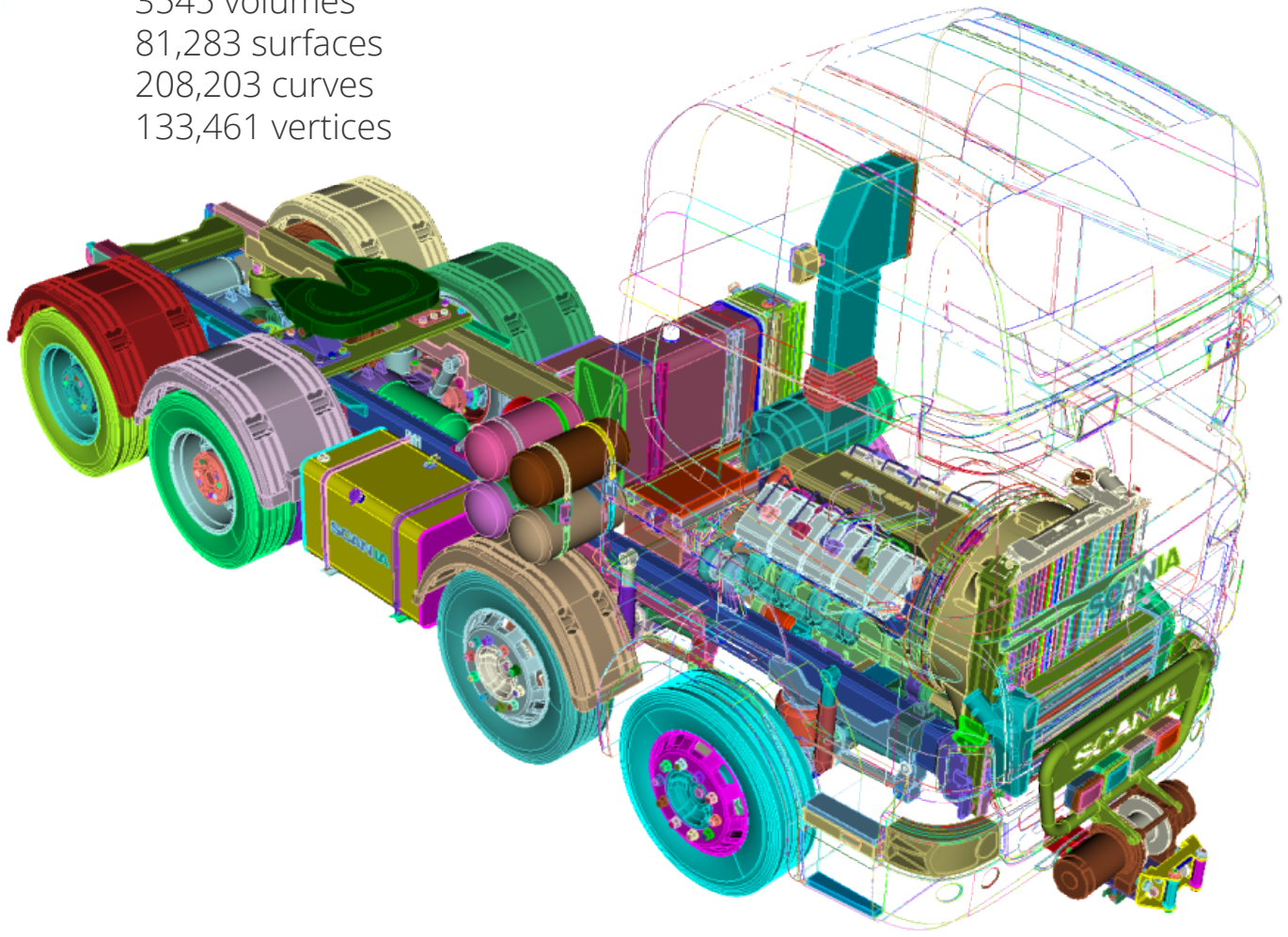


Example workflow

- Break into subsystems for teaming and/or avoid large model size
- Remove parts that are irrelevant and not normally modeled for a specific physics
- Fix bad geometry
- Remove small features
- Remove gaps, overlaps, misalignments
- Tet mesh
- Identify and prepare specific categories of mechanisms (Bolts, Springs, Bearings, etc.)
- Compute preloads on bolts, springs, etc.
- Prepare input deck

Rapid CAD to Simulation with Machine Learning

Commercial Truck CAD Model
3545 volumes
81,283 surfaces
208,203 curves
133,461 vertices

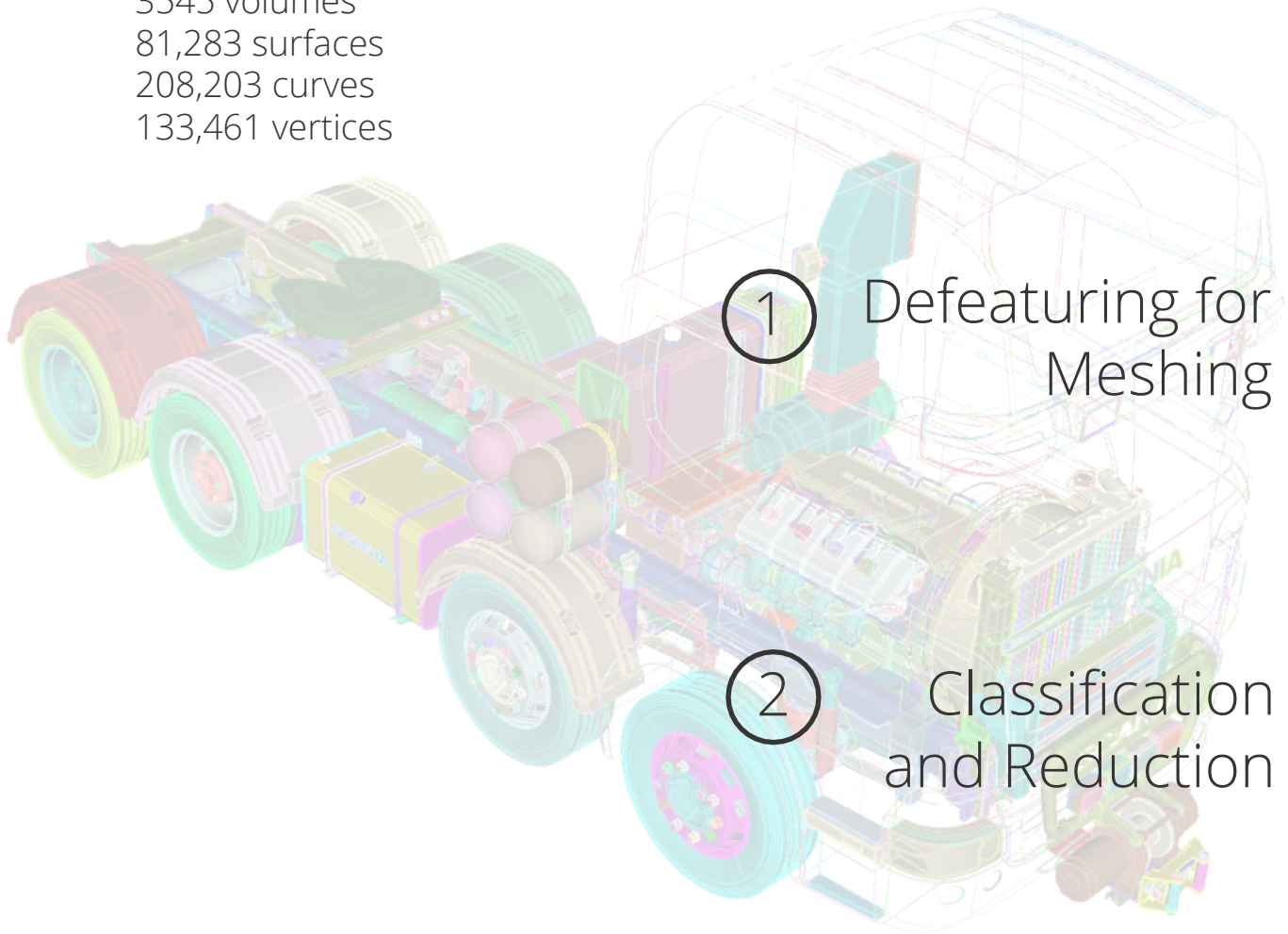


Machine Learning for Analysis Preparation:

- Reduce/Eliminate most tedious tasks
- Guide user to next step
- Present user with smart options
- User validates ML-solutions
- Standardization between analysts

Rapid CAD to Simulation with Machine Learning

Commercial Truck CAD Model
3545 volumes
81,283 surfaces
208,203 curves
133,461 vertices



Example workflow

- Break into subsystems for teaming and/or avoid large model size
- Remove parts that are irrelevant and not normally modeled for a specific physics
- Fix bad geometry
- Remove small features
- Remove gaps, overlaps, misalignments
- Tet mesh
- Identify and prepare specific categories of mechanisms (Bolts, Springs, Bearings, etc.)
- Compute preloads on bolts, springs, etc.
- Prepare input deck

Machine Learning driven Defeaturing

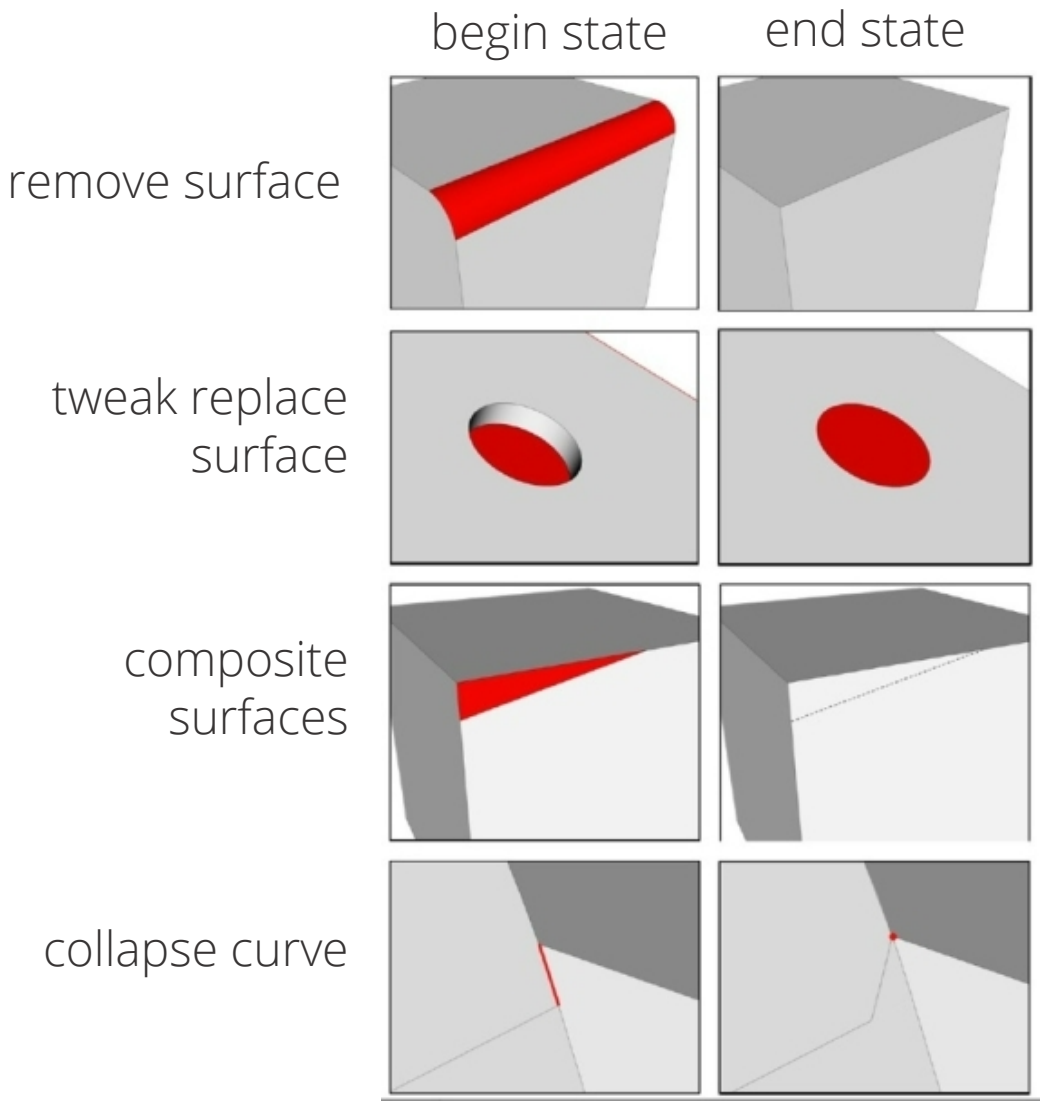
1 Find the most problematic features in the CAD Model

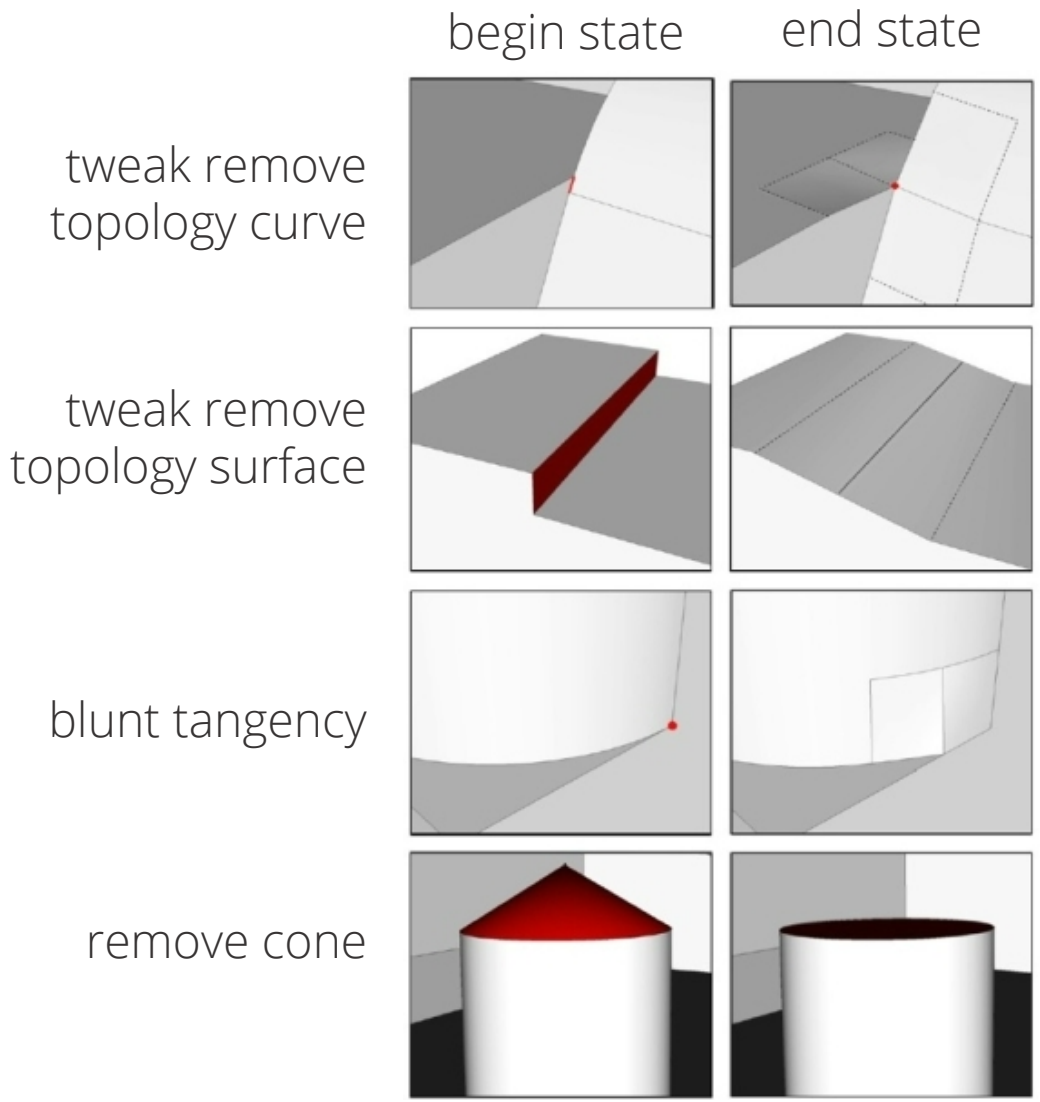
- For a given local topology
  - Small Curve
  - Small Surface
  - Sharp Angle at Vertex
- Predict local mesh quality
  - Scaled Jacobian
  - In-Radius
  - Deviation

2 Find solution that yields best mesh quality

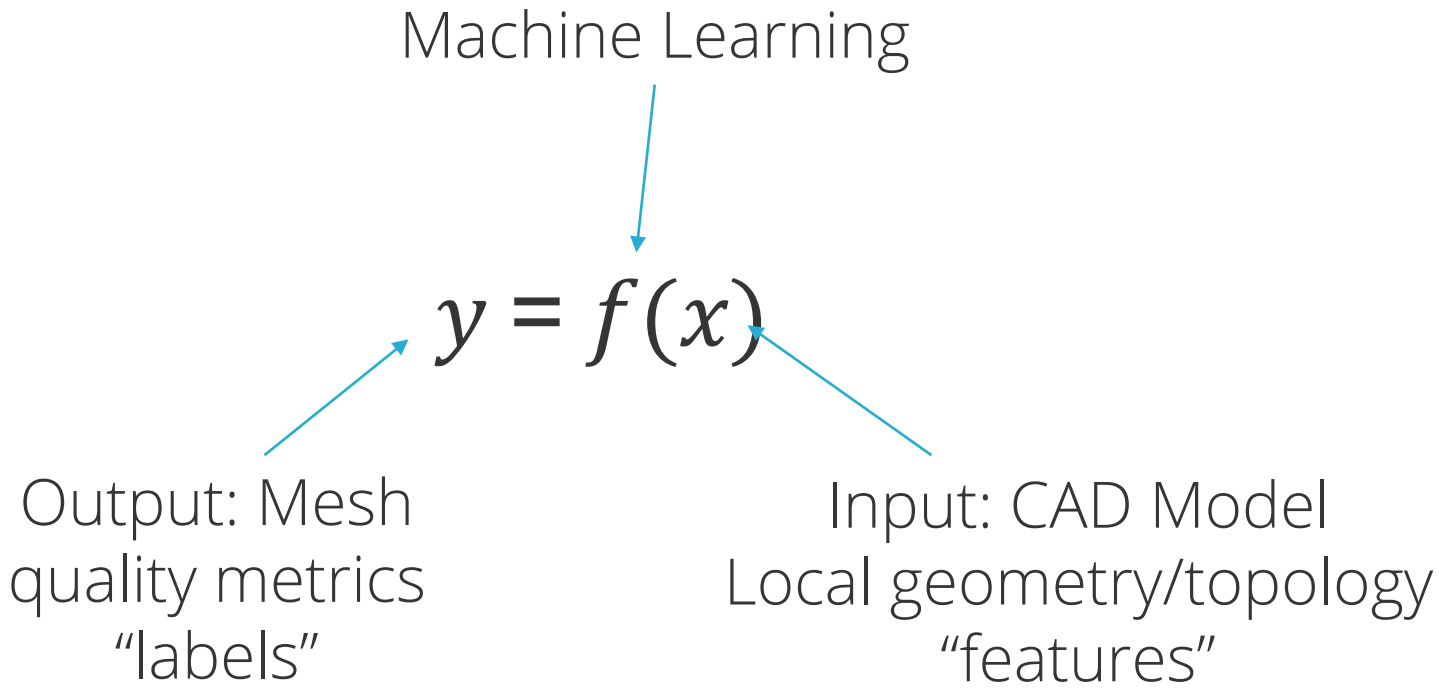
- For a given local geometry operation
  - Collapse Curve
  - Remove Surface
  - Blunt Tangency
  - Etc..
- Predict local mesh quality after operation
  - Scaled Jacobian
  - In-Radius
  - Deviation

Example defeaturing operations





Machine Learning for Defeaturing



Machine Learning for Defeaturing

xy → f → $y = f(x)$

Training Data
.csv file

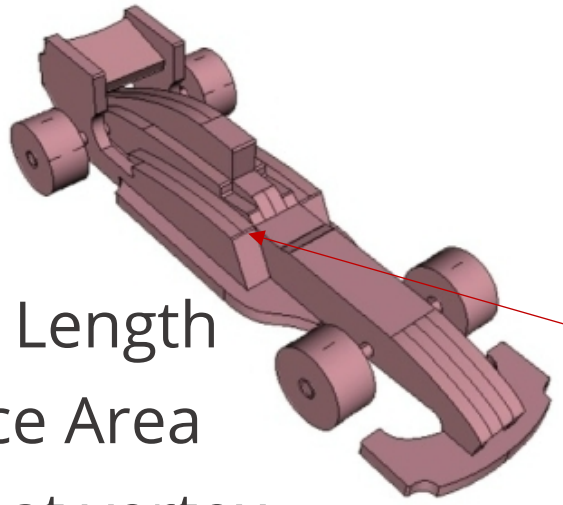
- Characterize *problems*
  - Features
  - Labels
- Python Script + Cubit
- Train many CAD models
- Diverse problems
- One row in .csv per *problem*
- Non-runtime

- scikit-learn
- Python open source
- Machine Learning libraries
- Many options and algorithms

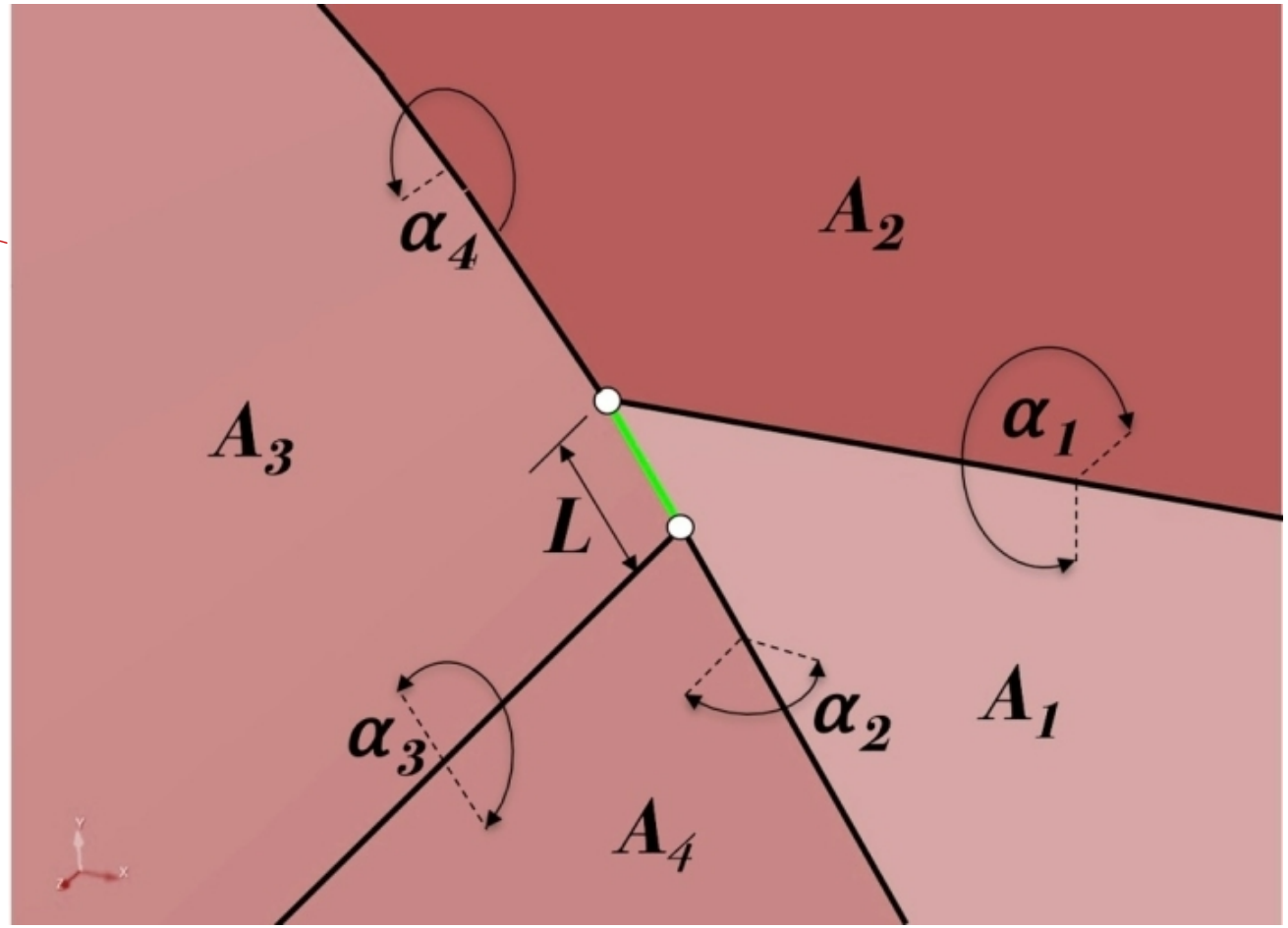
Machine Learning
Models

- Make predictions
- Small Binary
- Used Run-time in C++ Code
- Access via C-Python interface

Training Data Features

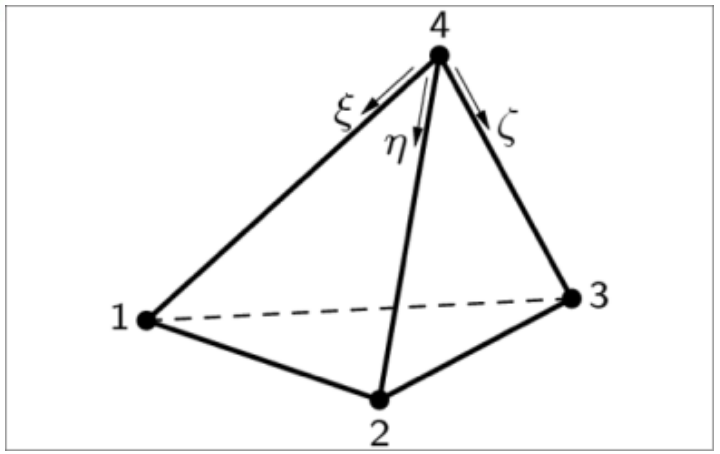


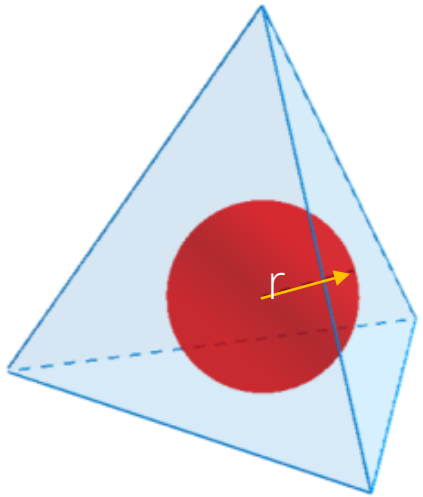
Curve Length
Surface Area
Angle at vertex
Angle at curves
Valence at vertex
Number of loops
Hydraulic Radius
Etc…

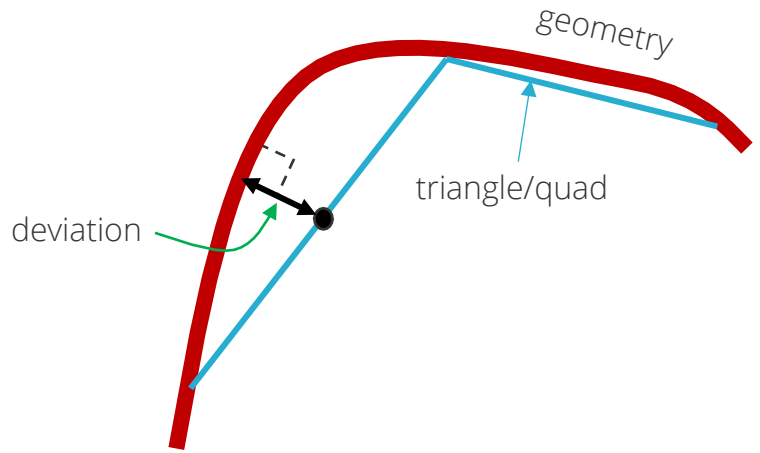


Topology-Based Features

Training Data Labels







Scaled Jacobian

- Function of angles at vertices
- Scaled -1.0 to 1.0
- Independent of mesh size

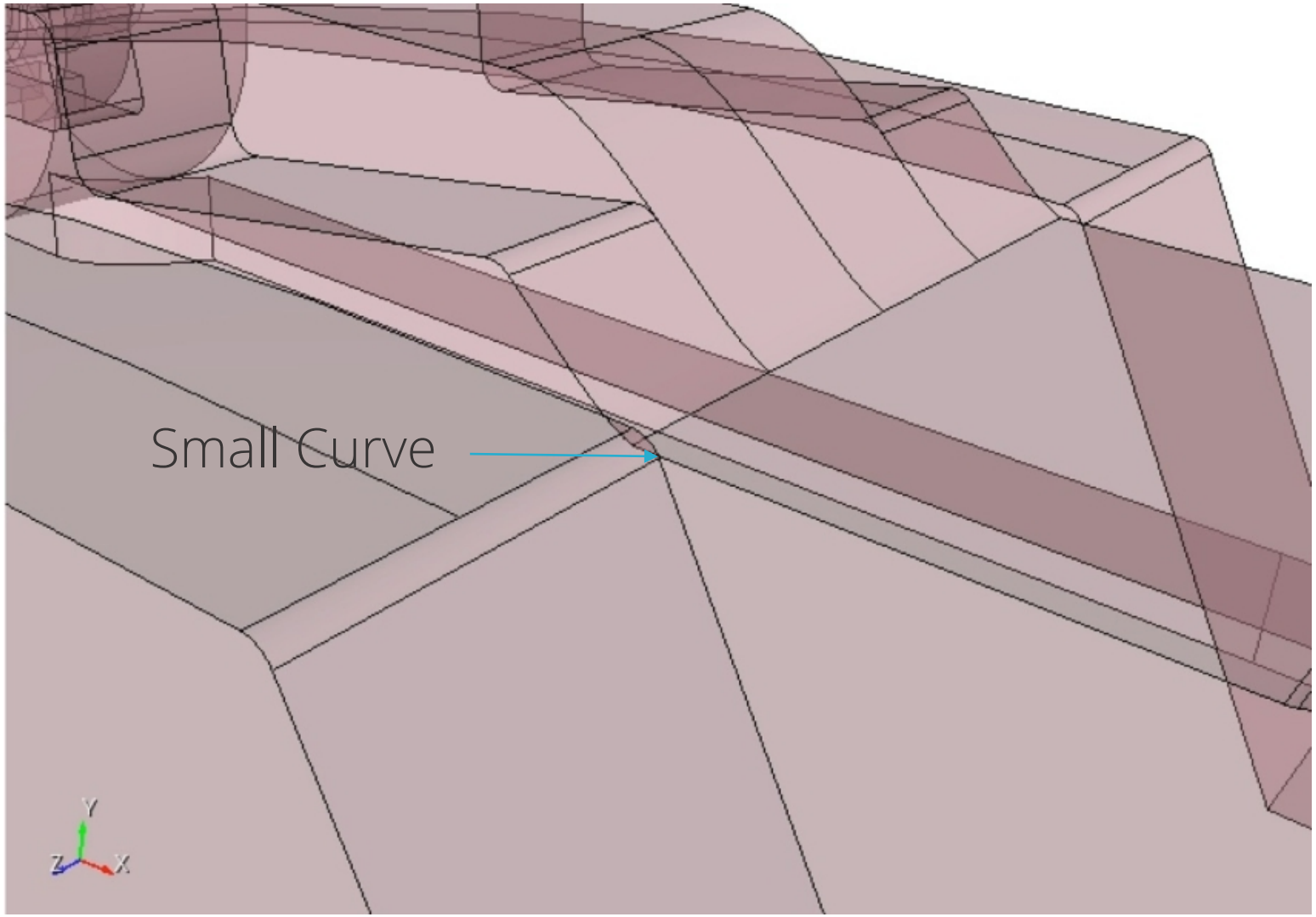
In-Radius Ratio

- Ratio with equilateral tet with target edge length
- Scaled 0.0 to 1.0
- Sensitive to mesh size

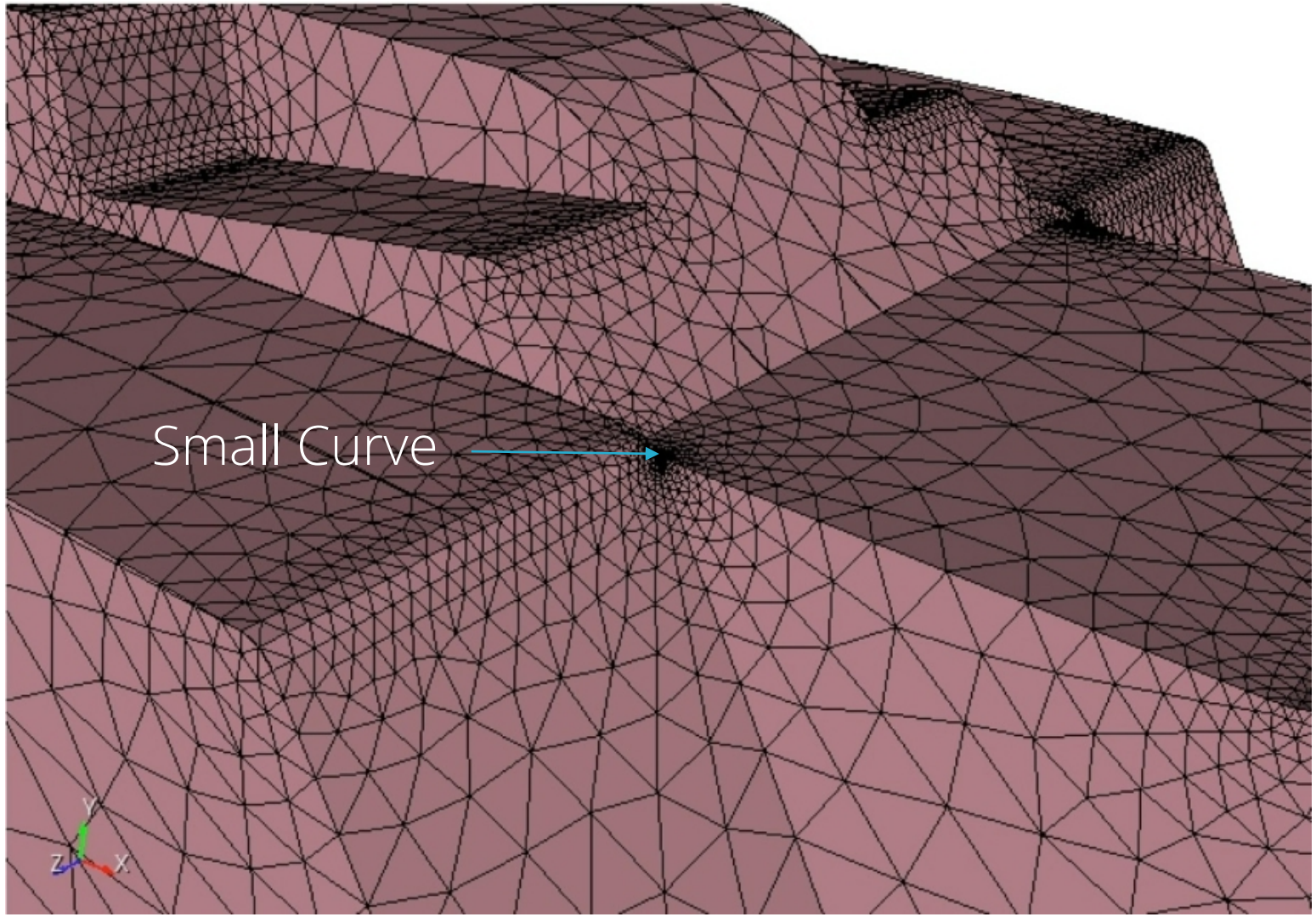
Deviation

- Distance from triangle centroid to closest point on geometry
- Scaled by target mesh size
- Ensure mesh "matches" geometry

Training Data Labels

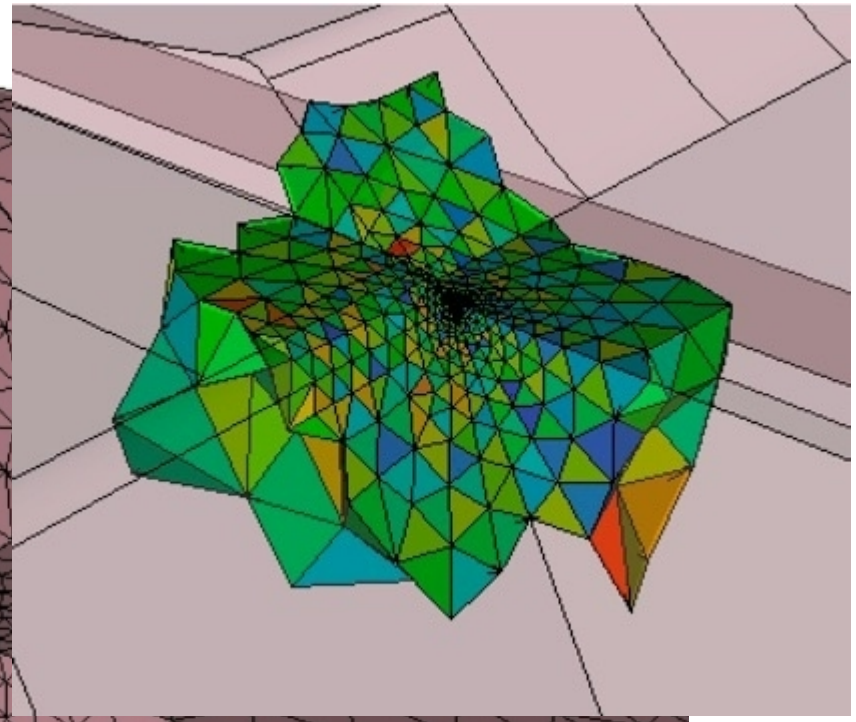


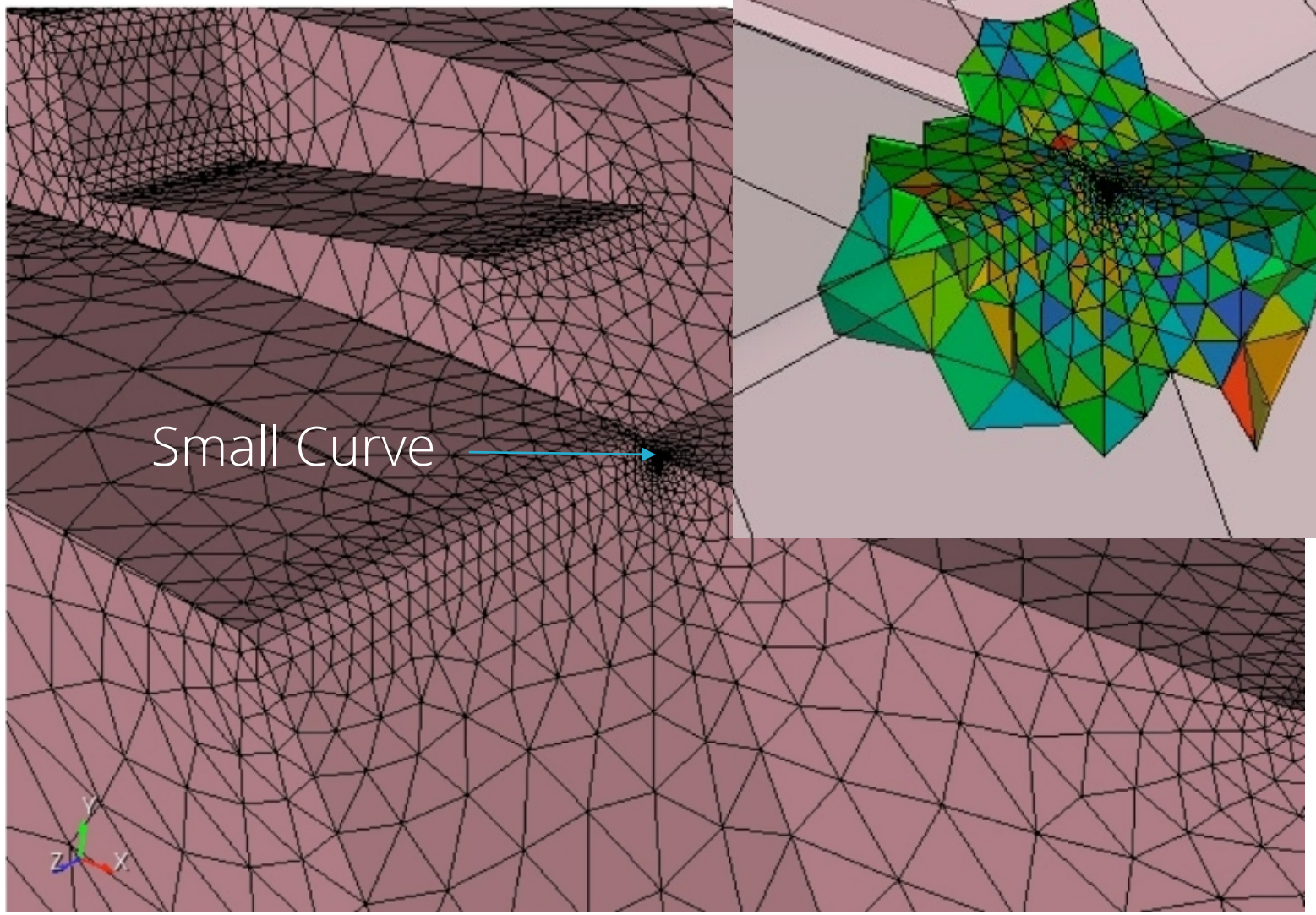
Training Data Labels



Training Data Labels

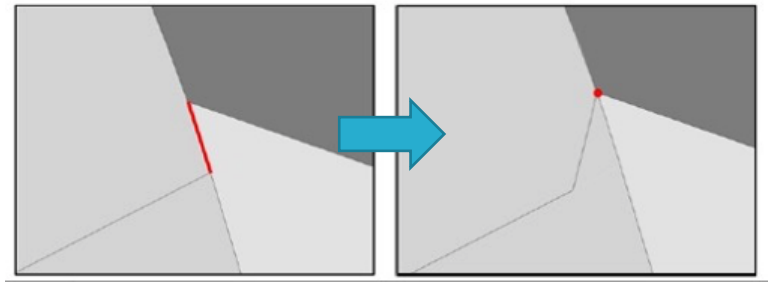
Local Tets at Geometric Curve





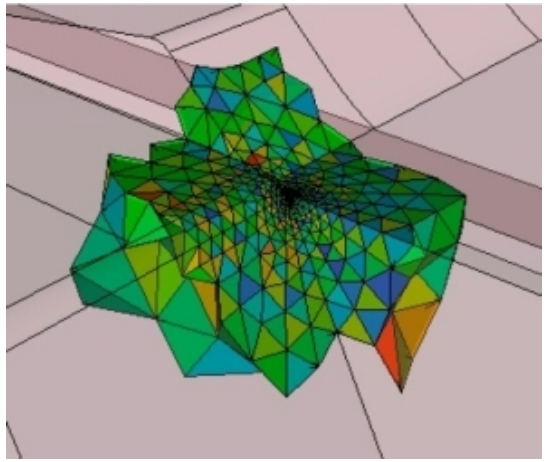
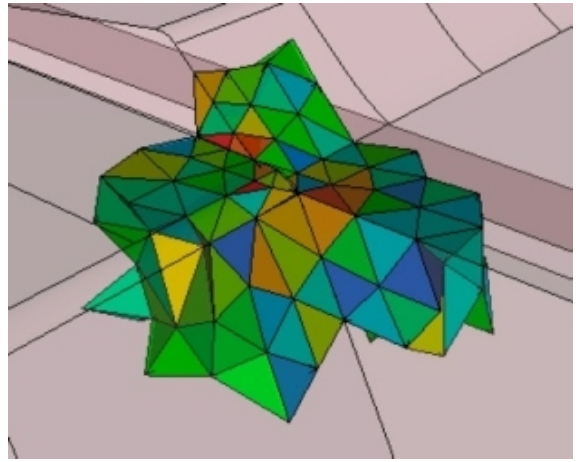
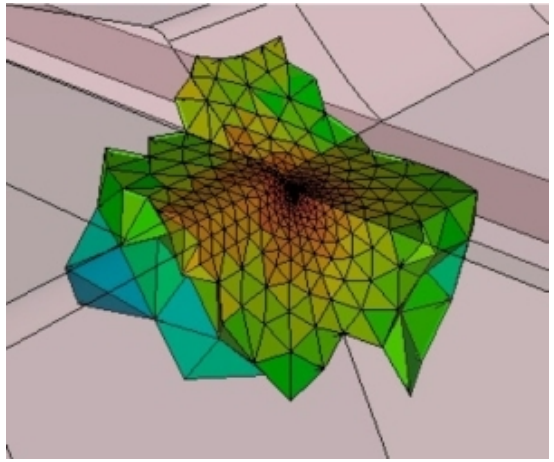
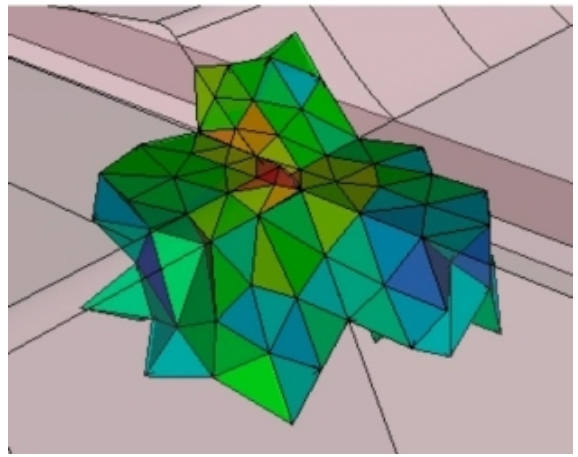
Training Data Labels

Collapse Curve

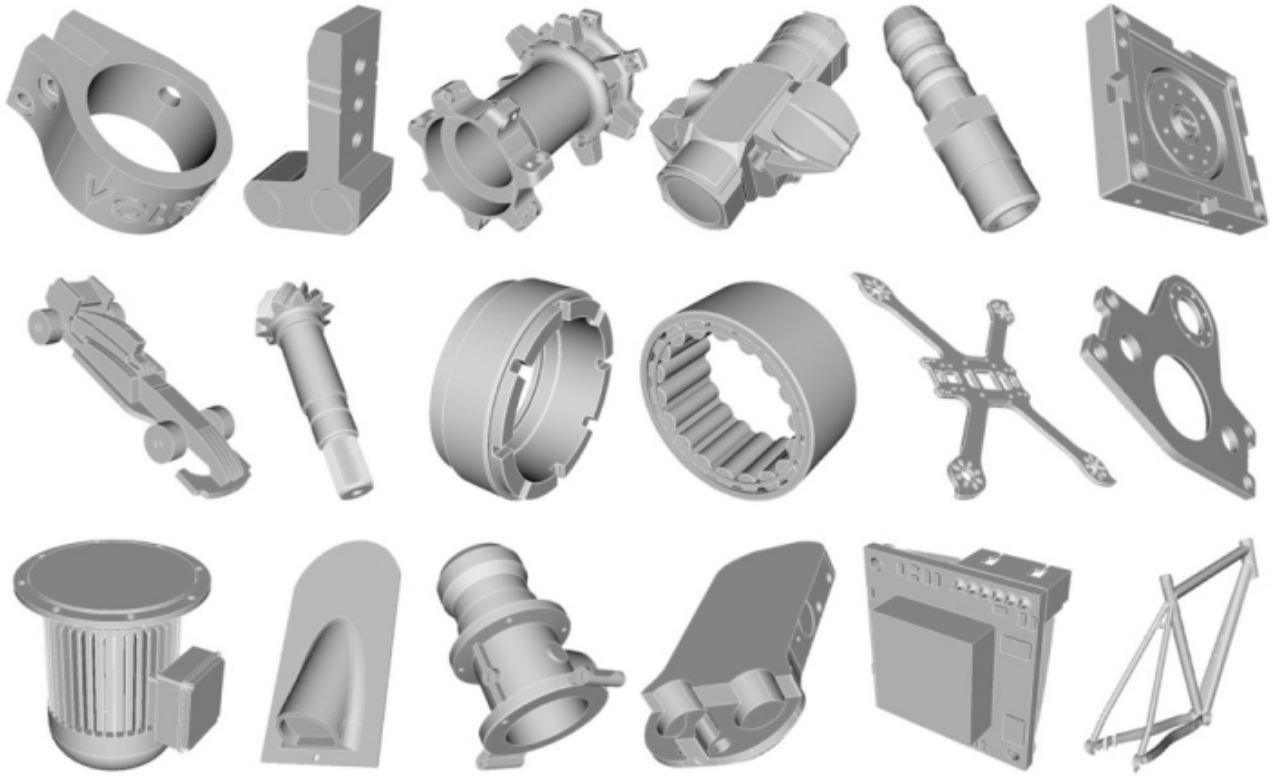


Before After

Collapse Curve

	Before	After
Scaled Jacobian	 Min SJ = 0.250	 Min SJ = 0.227
In-radius	 Min IR = 0.027	 Min IR = 0.267

Machine Learning Study



94 single-part CAD models

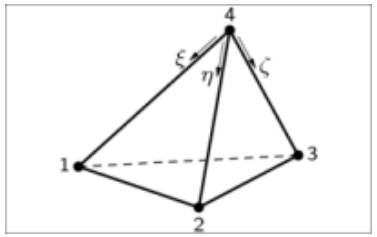
	Num Obs.	Num Failed	Num Trained
vertex_no_op	1348	0	1348
curve_no_op	9842	0	9892
surface_no_op	5842	0	5842
remove_surface	17,624	10,026	7598
tweak_replace_surface	2569	1152	1417
composite_surfaces	43,551	5020	38,531
collapse_curve	13,830	2113	11,717
virtual_collapse_curve	14,955	14,743	212
remove_topology_curve	7056	5175	1881
remove_topology_surface	3890	3102	788
blunt_tangency	8059	3982	4077
remove_cone	232	20	212
Totals	**128,484**	**45,333**	**83,515**

Owen, Steven; Shead, Timothy M.; Martin, Shawn , "CAD Defeaturing Using Machine Learning", *28th International Meshing Roundtable (IMR)*, Buffalo, New York, USA, October 14-17, 2019

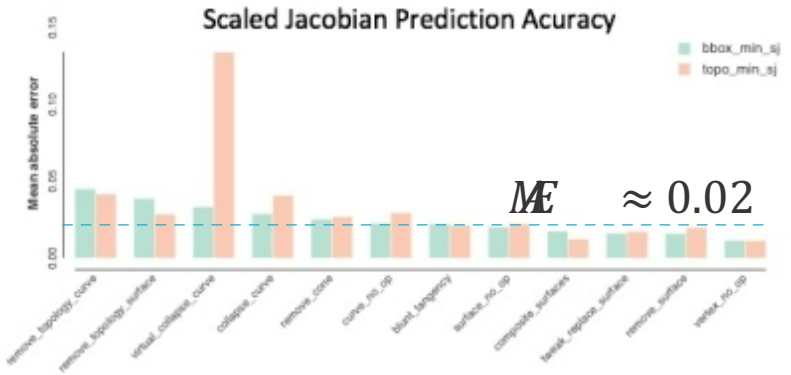
Patent Pending Application 17/016, 542 September 10, 2020

Machine Learning Study – EDT (Ensembles of Decision Trees)

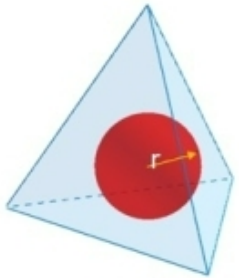
Scaled Jacobian

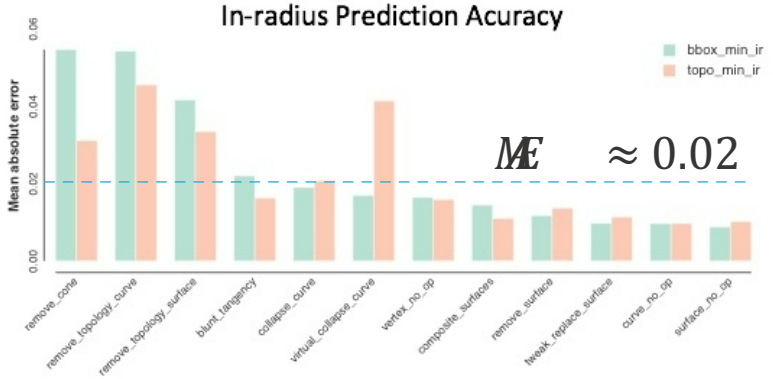


Mean Absolute Error (MAE)

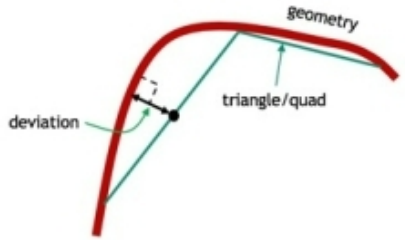


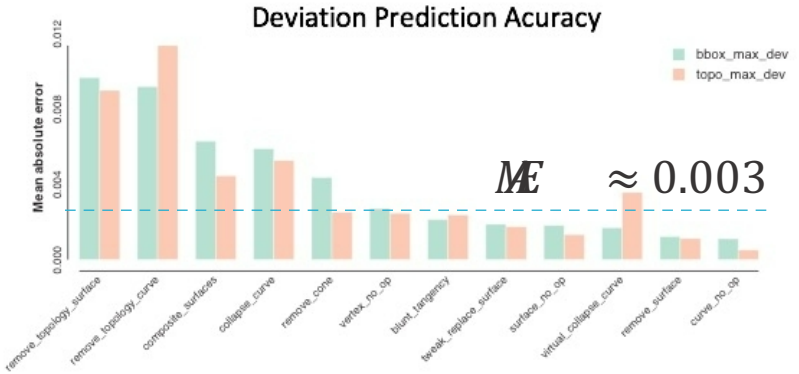
Scaled In-radius



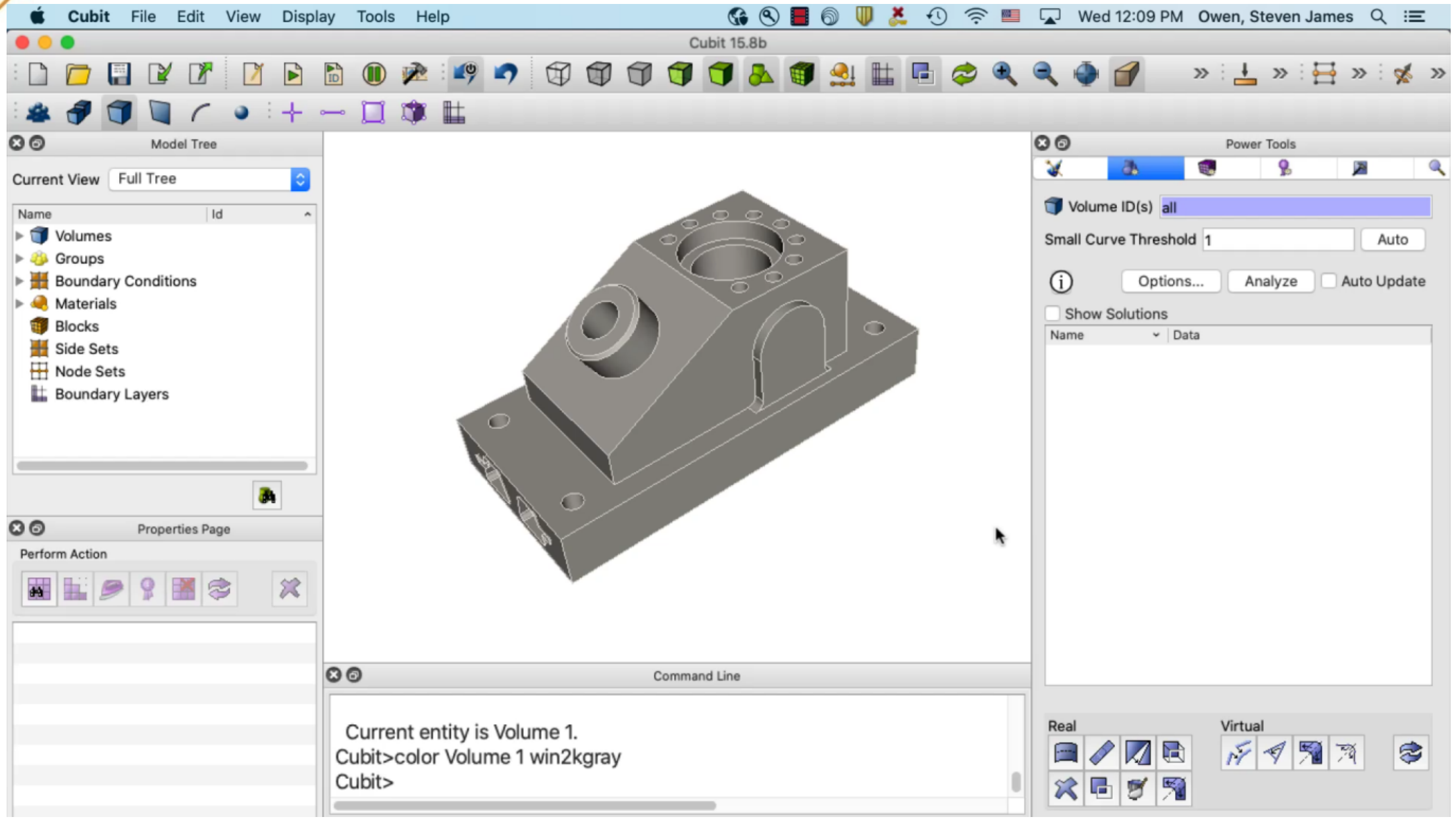


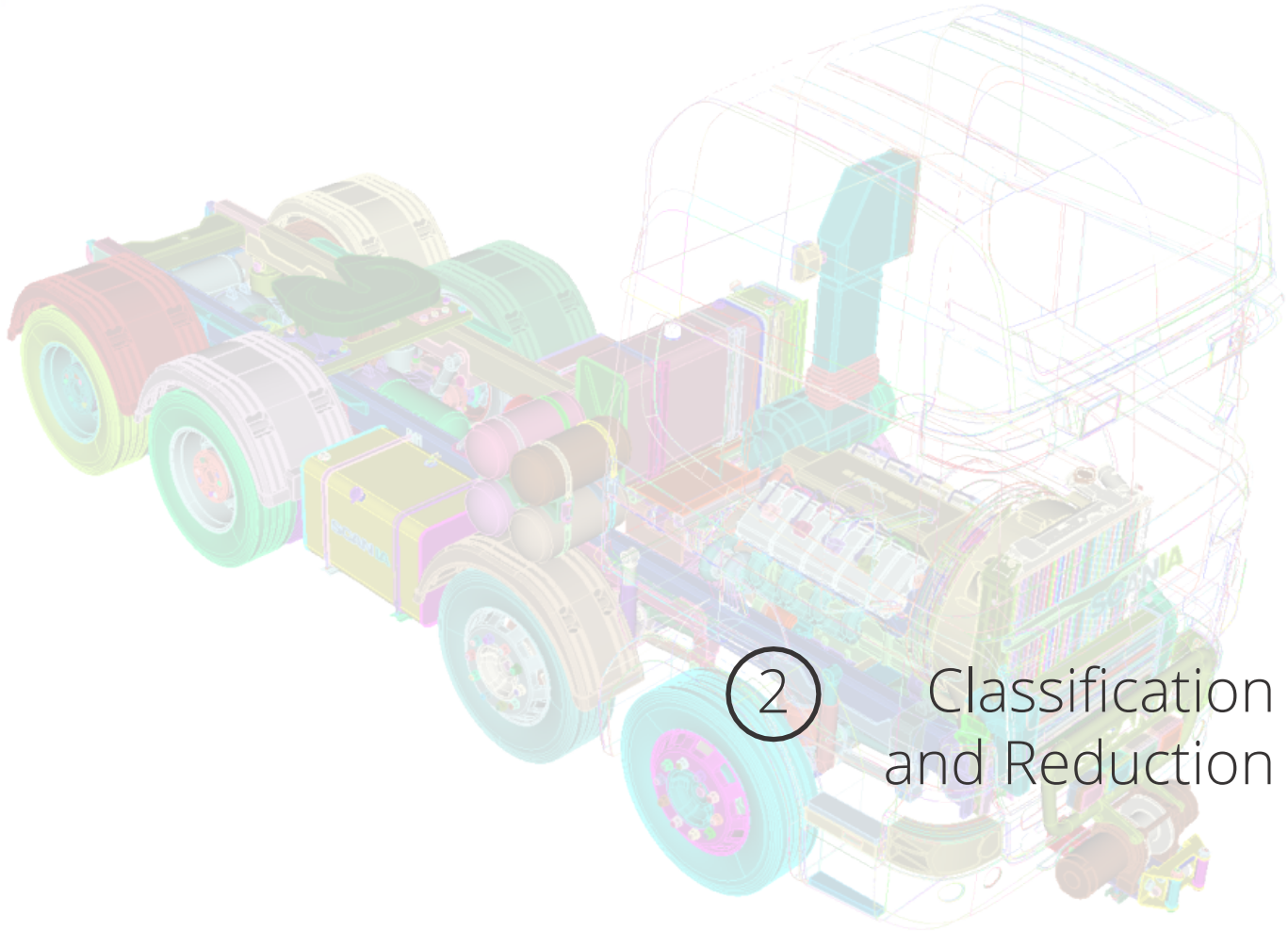
Scaled Deviation





Defeaturing for Meshing Example



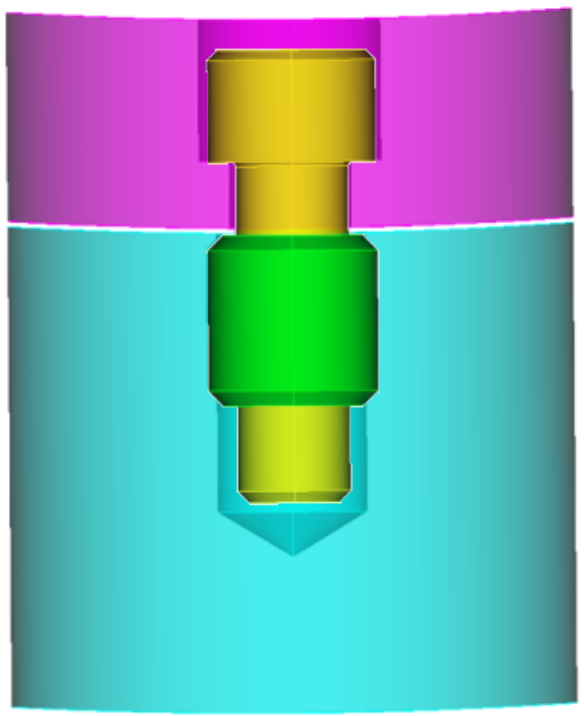


Example workflow

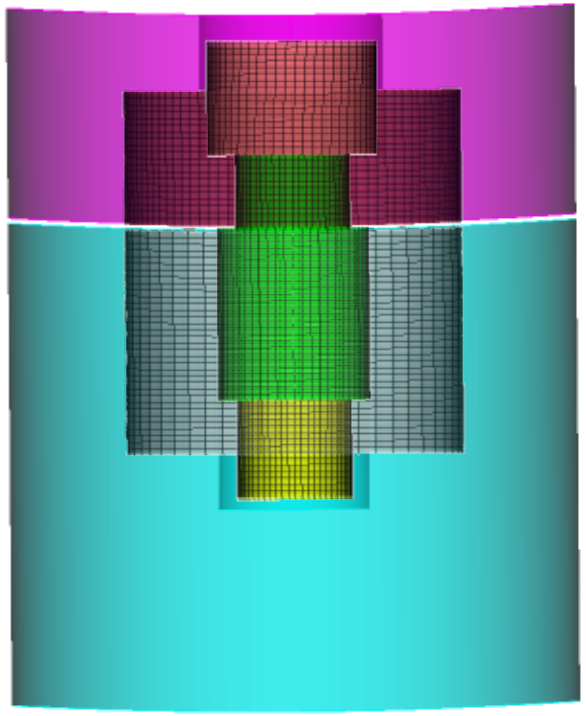
- Break into subsystems for teaming and/or avoid large model size
- Remove parts that are irrelevant and not normally modeled for a specific physics
- Fix bad geometry
- Remove small features
- Remove gaps, overlaps, misalignments
- Tet mesh
- Identify and prepare specific categories of mechanisms (Bolts, Springs, Bearings, etc.)
- Compute preloads on bolts, springs, etc.
- Prepare input deck

Mechanism Part Classification

Classify Common Mechanisms → Rapidly Prepare for Analysis

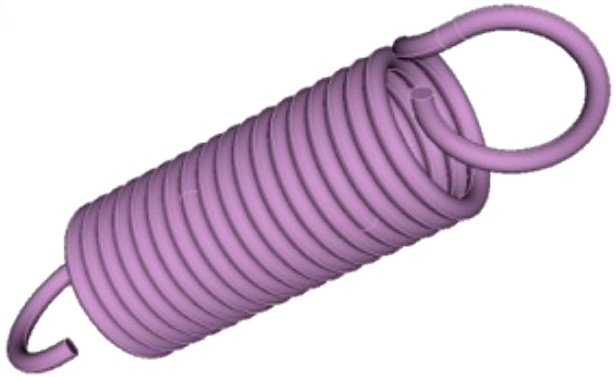


Bolt in CAD assembly before preparation



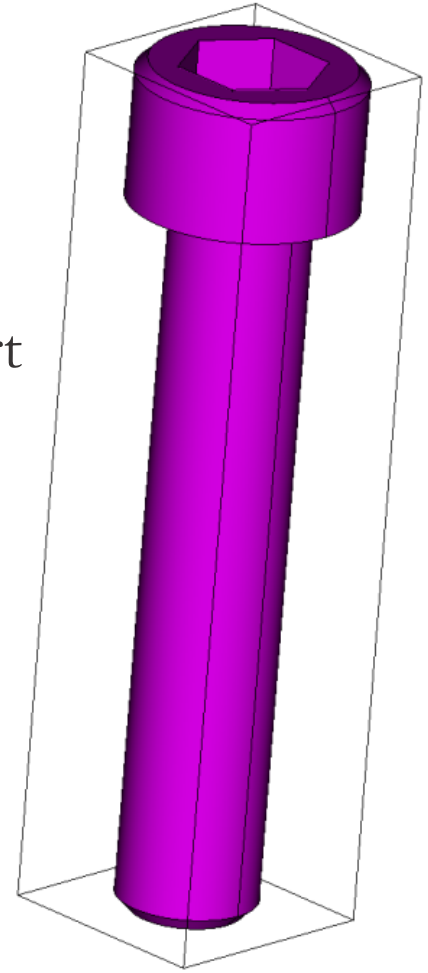
Bolt ready for analysis

Mechanism Part Classification - Features



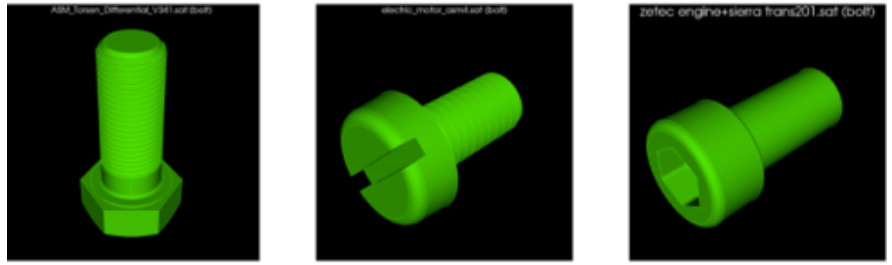
Features of a CAD Volume

- Genus
- Min aspect ratio
- Max aspect ratio
- Tight Bounding Box Volume / Volume of Part
- Principal Moments
- Area of Surfaces / Volume of Part
- Ratio of Cylindrical Surface Area
- Ratio Planar Surface Area
- Ratio High Curvature Surfaces
- Ratio of exterior curve angles 90 degrees
- Ratio of exterior curve angles 180 degrees
- Ratio of exterior curve angles 270 degrees
- Etc...

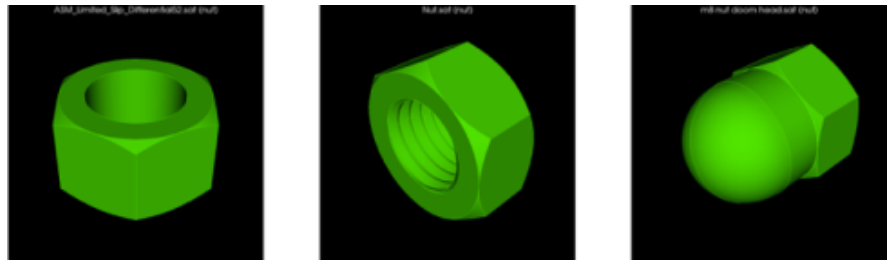


Mechanism Part Classification - Labels

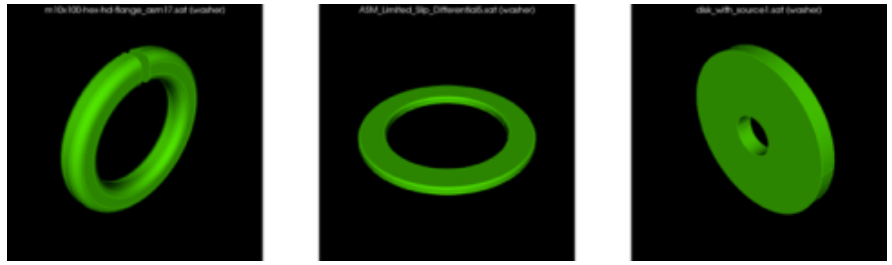
Bolt



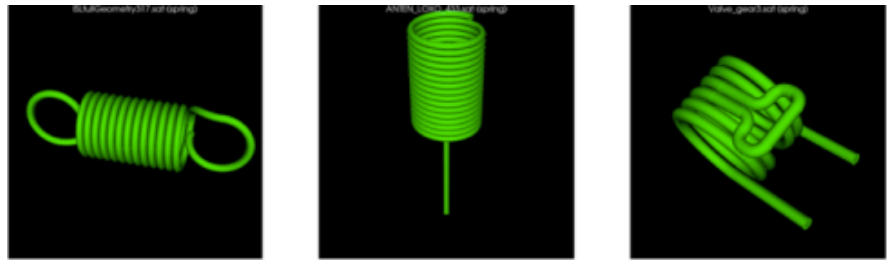
Nut



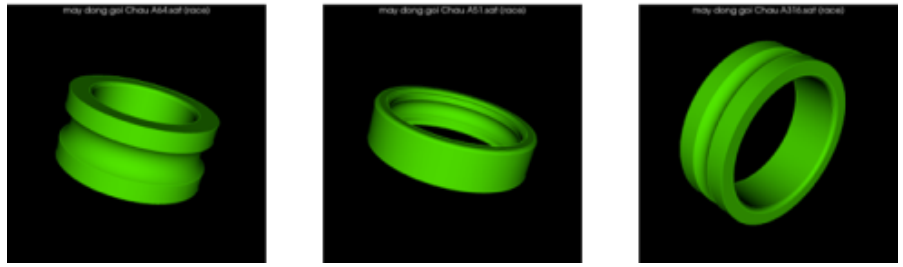
Washer



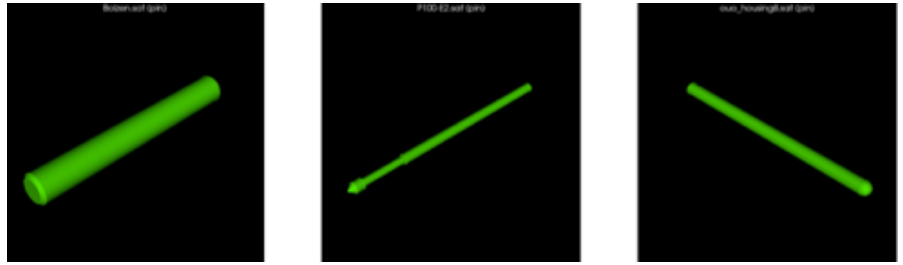
Spring



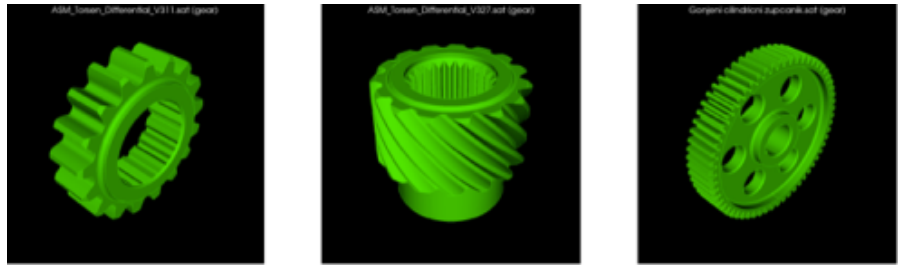
Race



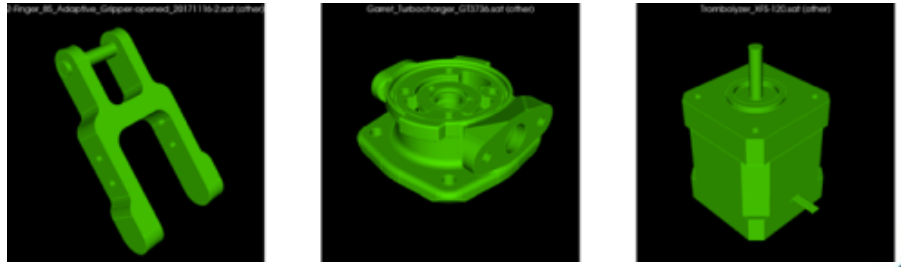
Pin



Gear



Other



Mechanism Part Classification - Accuracy

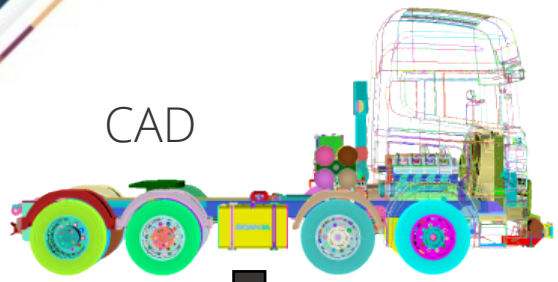
label	precision	recall	support
is_bolt	98.1%	98.3%	423
is_nut	95.5%	82.4%	44
is_washer	95.7%	97.8%	92
is_spring	100.0%	100.0%	34
is_ball	100.0%	100.0%	262
is_race	95.2%	100.0%	83
is_pin	97.8%	98.3%	180
is_gear	99.0%	89.9%	99
is_other	97.3%	98.1%	1033
Total			2250

Ensembles of Decisions Trees
with 5X2 cross validation

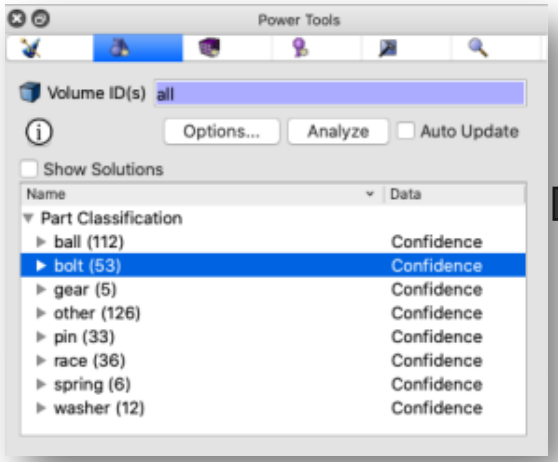
Models Source: -OUO Models from Sandia Analysts
-GrabCAD Open Source Repository

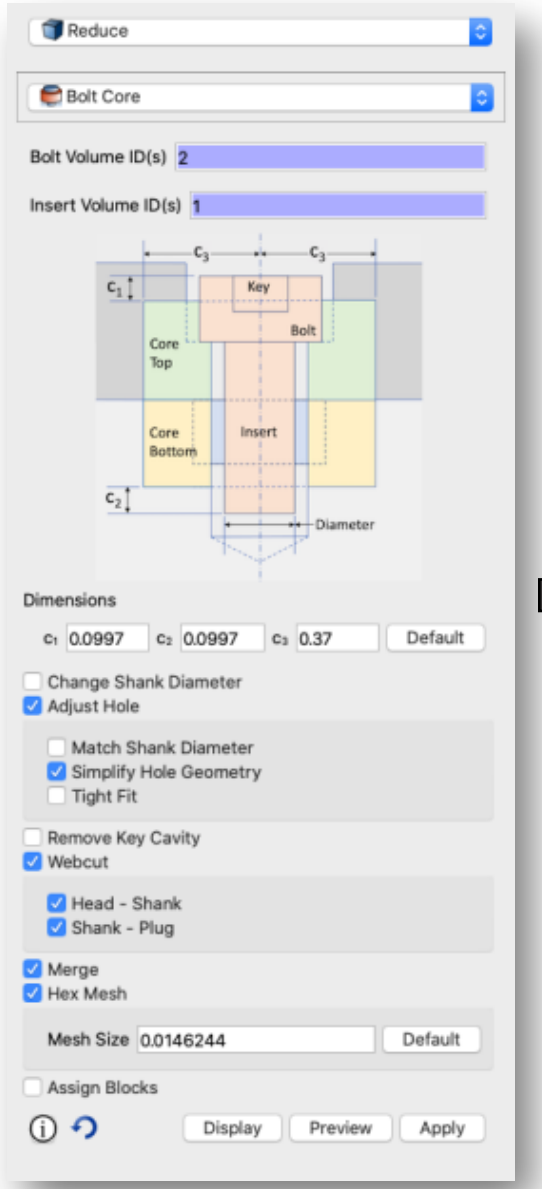
Reduce for Simulation (Fasteners)

CAD



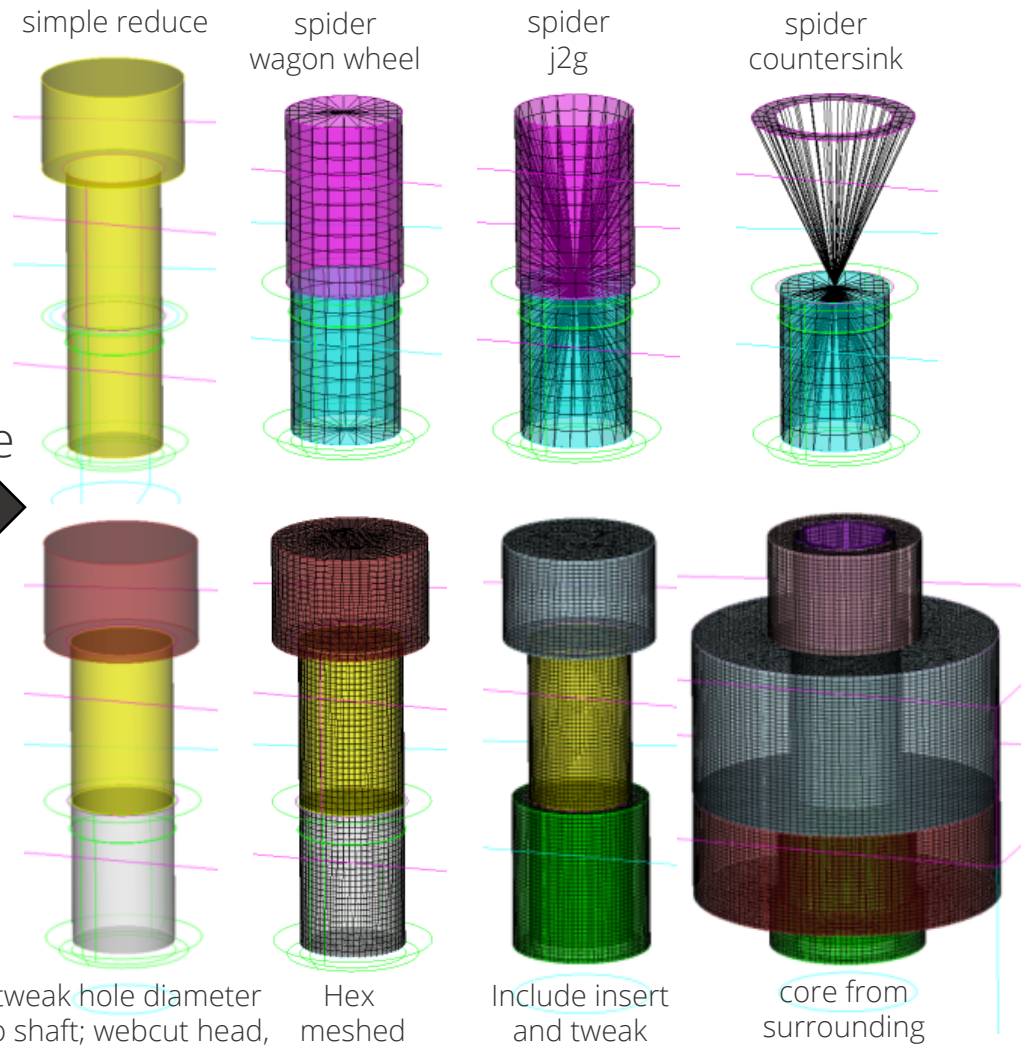
classify





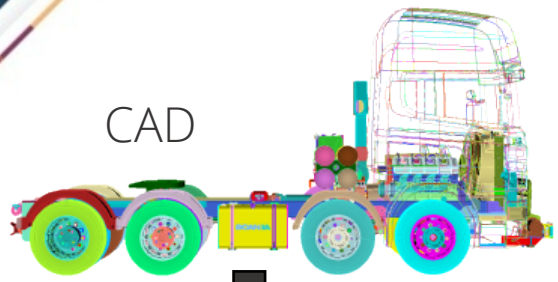
reduce

simulation-ready

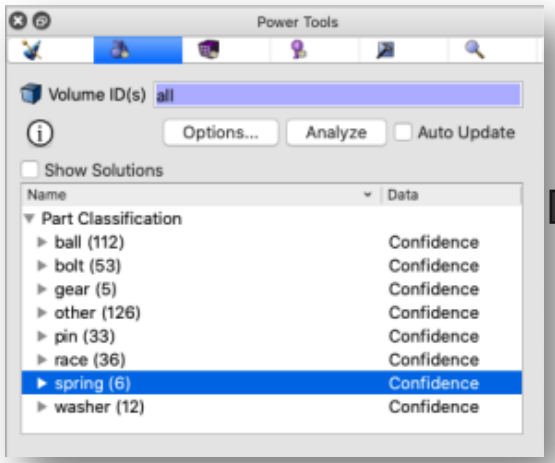


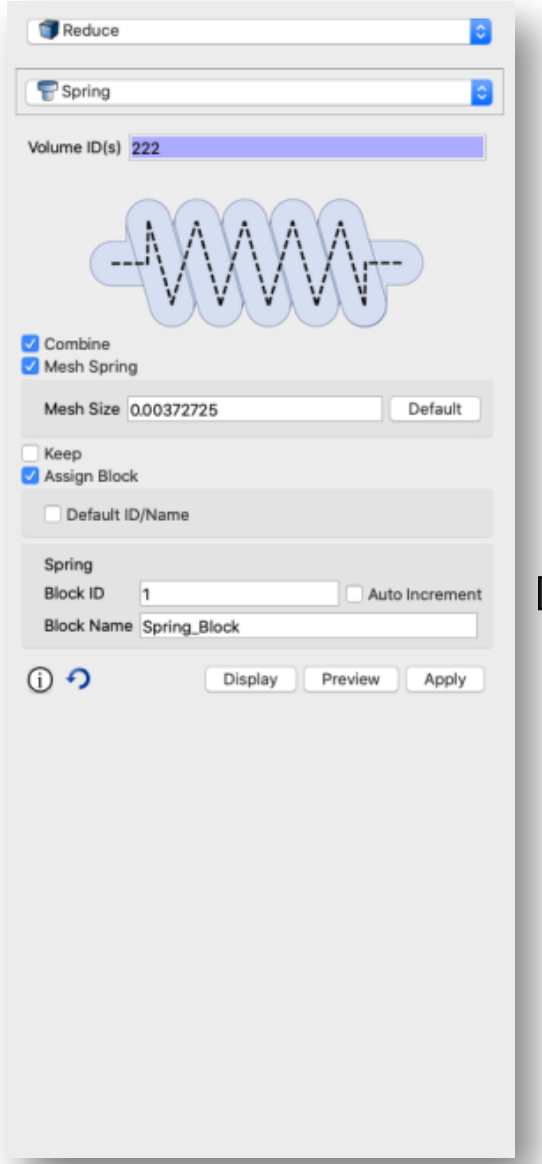
Reduce for Simulation (Springs)

CAD



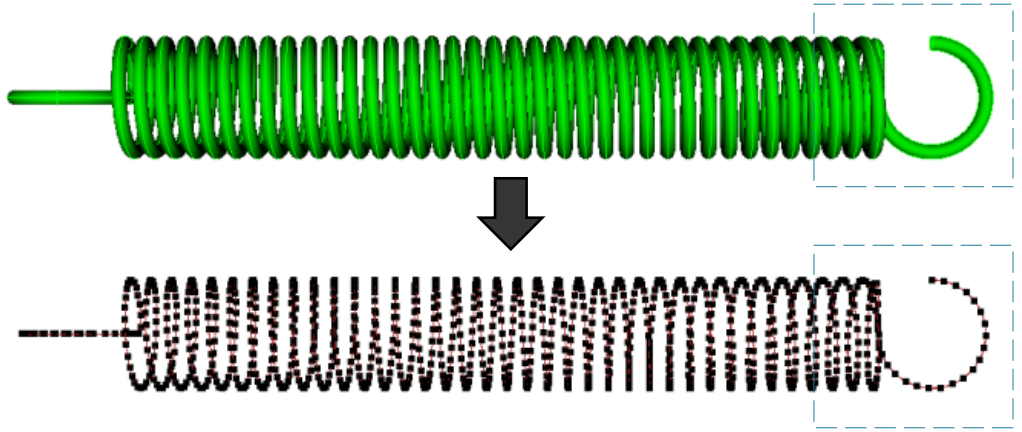
classify

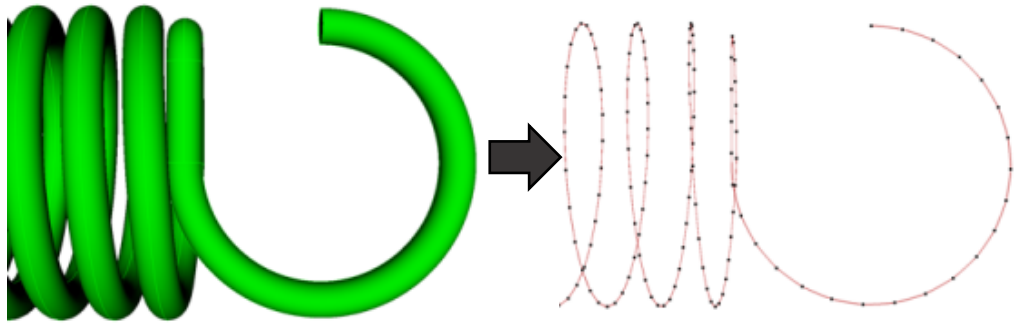




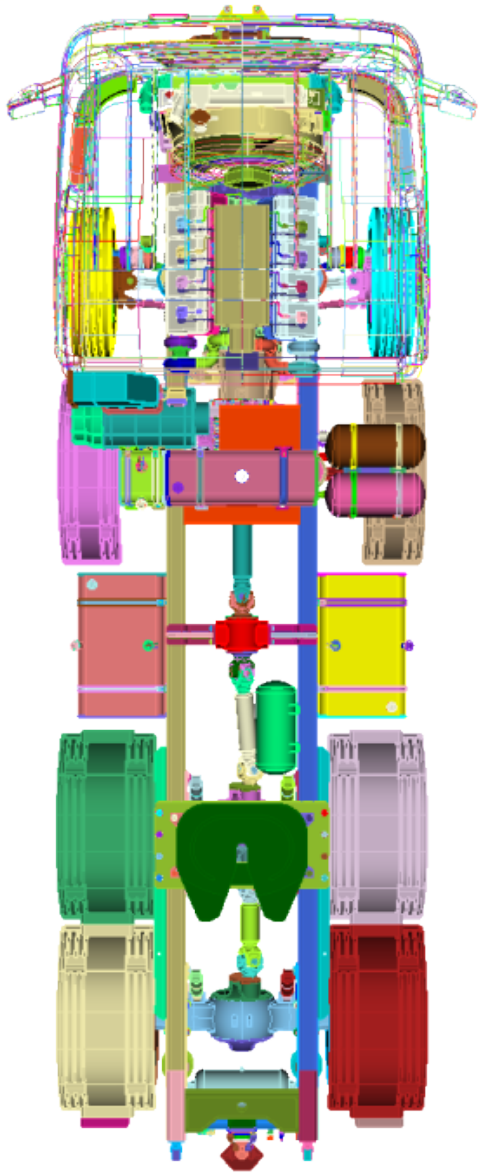
reduce

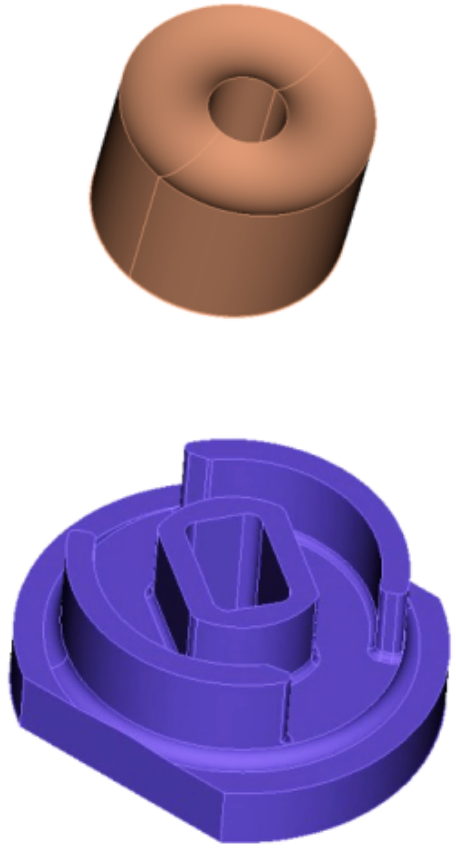
simulation-ready





In-situ user driven training





User-defined parts

In-situ user driven training

All available training data

Apply learning algorithm

Finished Model
with N categories

Make many predictions

"Normal" developer driven training

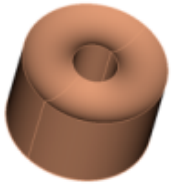
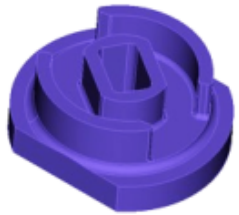
New category examples

Existing Model
with N categories

Extend model and
apply learning algorithm

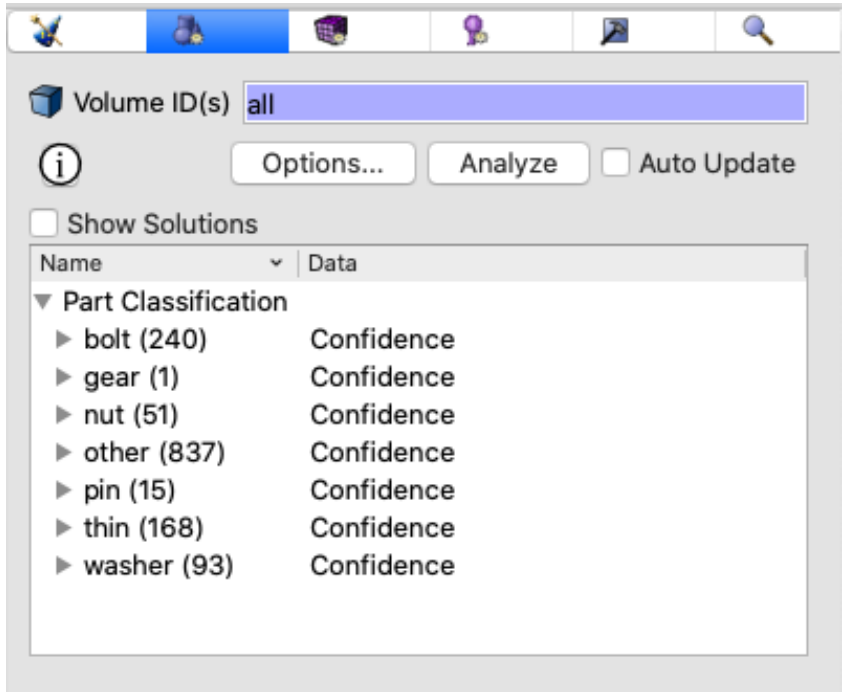
New Model
with N+1 categories

Make predictions

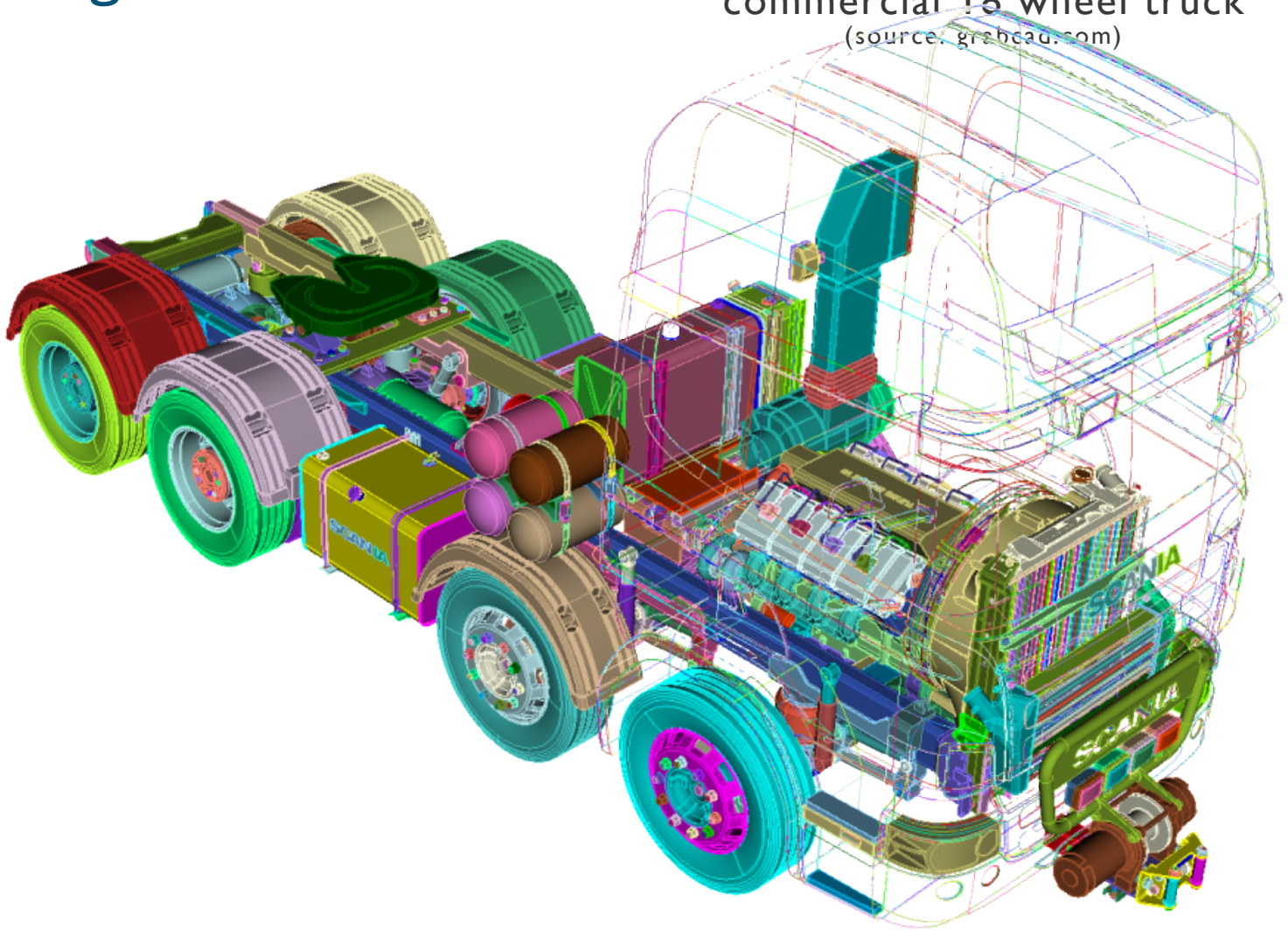
Online user driven training

In-situ user driven training



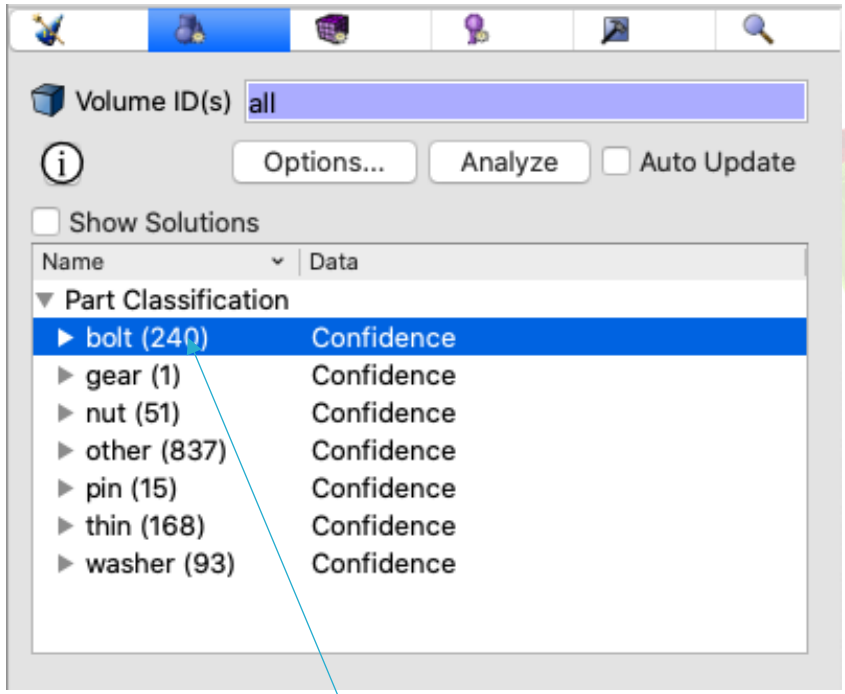
1048 parts classified into
7 categories

CAD assembly of
commercial 18 wheel truck
(source: grabcad.com)

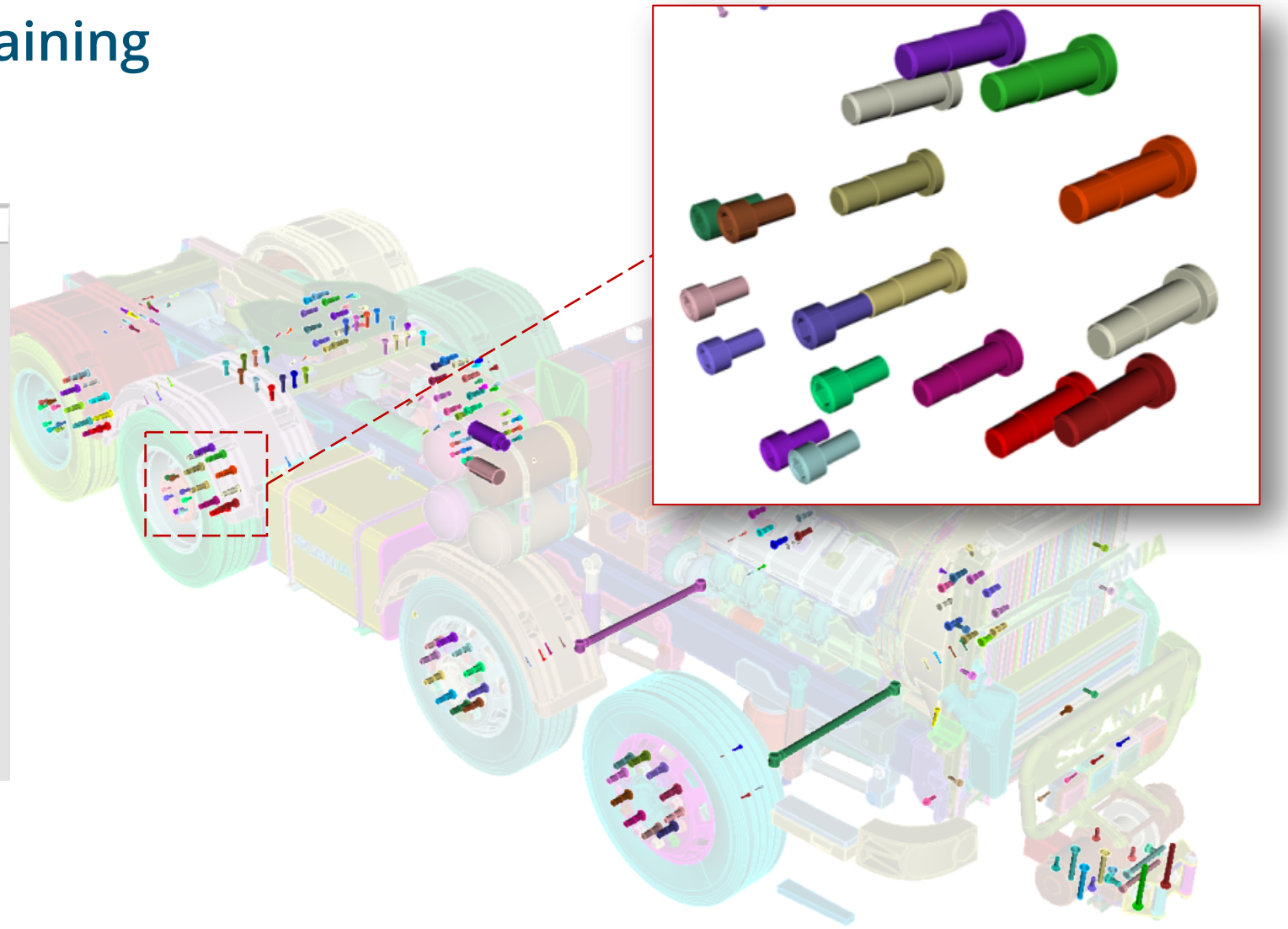


3D Solid Model: Full Assembly
(1048 Solid Volumes)

In-situ user driven training

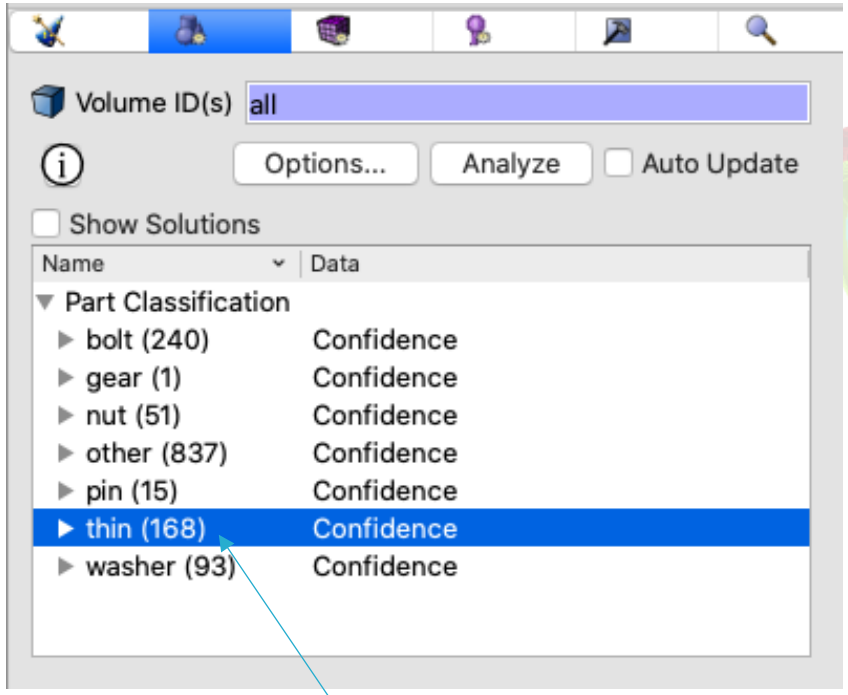


Existing "**bolt**" category
Classified 240 bolts



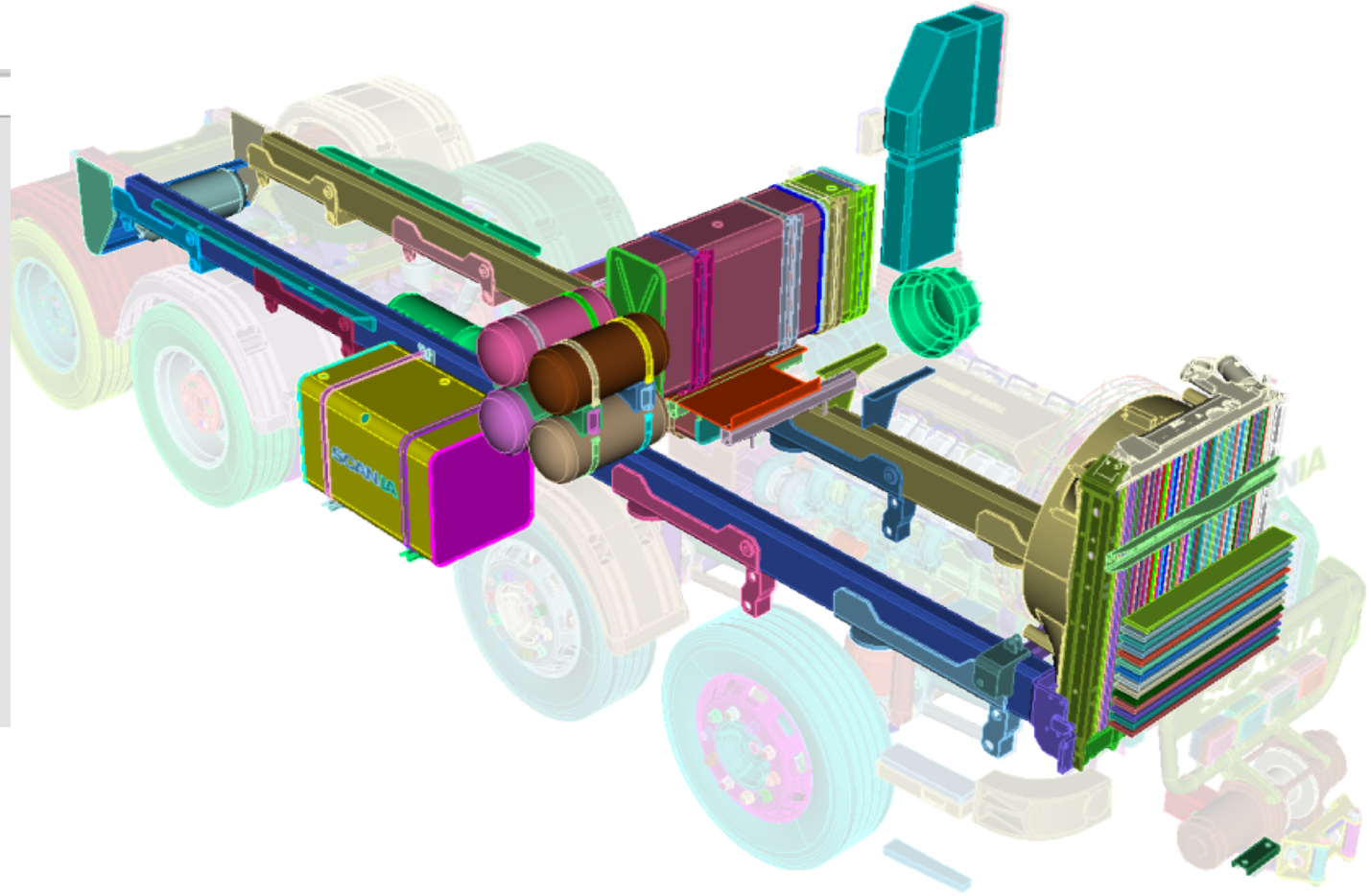
3D Solid Model: "Bolt" Volumes Only
(240 Volumes)

In-situ user driven training



New user-defined "thin" category
Classified 168 thin volumes

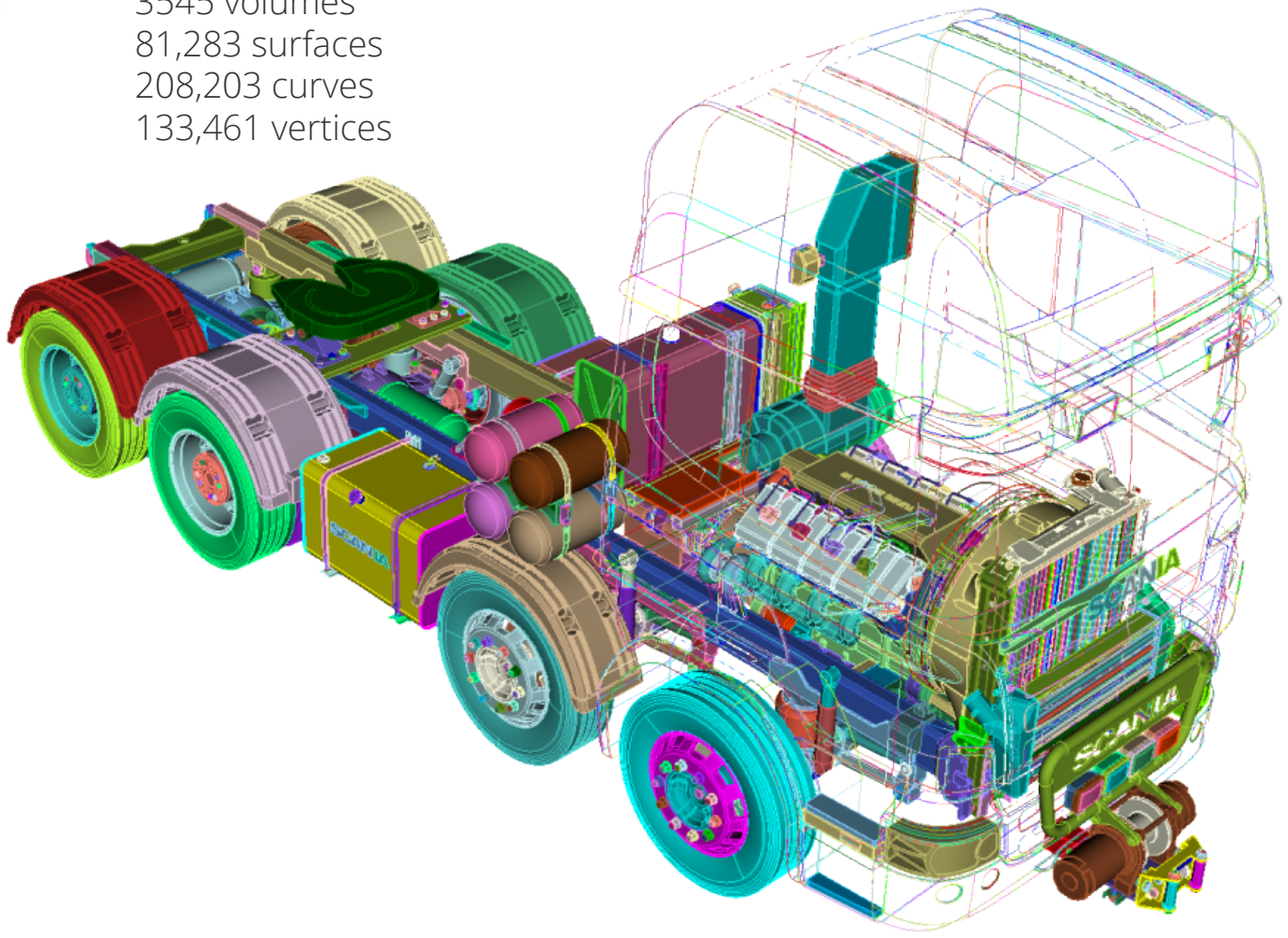
CAD assembly of
commercial 18 wheel truck
(source: grabcad.com)



3D Solid Model: "Thin" Volumes
Only
(168 Volumes)

Rapid CAD to Simulation with Machine Learning

Commercial Truck CAD Model
3545 volumes
81,283 surfaces
208,203 curves
133,461 vertices



Machine Learning for Analysis Preparation:

- Defeaturing
  - Predicts potential problems in mesh
  - Predicts tools that will best improve
  - Allows user to select and validate
- Part Classification
  - Identifies common mechanism types
  - Tools to quickly reduce to analysis-ready
  - In-situ training on user-defined categories

What's next

- New analyst-driven custom **reduce** solutions
- Reinforcement Learning
- ML-driven Beam and Shell Modeling