CAD/CAM
MSc. Course / Production Engineering

Solid Modeling

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Solid model (Since early 1990’s):

Objects are defined as a solid mass. May contain information about the density, mass, moment of inertia, volume and center of gravity of the object.

**Solid Modeling features:**
- Most complex
- Complete representation
- Unambiguous description
- Appropriate for the world of engineering objects

**Solid models can be used for:**
- Volume calculations.
- Automatic Finite Element mesh generation.
- Collision determination in robotics or NC path generation.

**Solid modeling entities**

- **Construction Solid Geometry (CSG)** [assemble model from primitives]
  - Solid primitives (cubes, spheres, cylinders, …….)
  - Boolean operations (Union, Subtraction, intersection)

- **Boundary Representation (B-Rep)** [Represent an object by dividing its surface into a series of “faces”]
  - Geometric entities (points, lines, surfaces, …….)
  - Topological entities (vertices, edges, faces, …….)

- **Sweep Representation**
  - Transitional sweep (Extrusion)
  - Rotational sweep (Revolution)
Decomposition Modeling

a) **Exhaustive Enumeration:** All space is evenly blocked out & a 3D matrix stores information on the material (or lack of) in each block

b) **Cellular Decomposition:** Irregular cells block out only the object

c) **Space Subdivision:** recursively block out all space.

**Exhaustive Enumeration:**

Special case of decomposition where primitives are *cubical* in shape

Uniformly-sized volume elements called **voxels**

Used extensively in computer graphics and medical graphics

Efficient but requires significant storage

Accuracy limited unless voxels are extremely small
Use of Voxel Representation In Casting

Here is another voxel representation. One can see how voxel representation is used in engineering for design and analysis. The voxels in these figures show the volumetric dimensions of the casting. In the first picture, the red regions represent regions of high or heavy stress. In the second picture, only the heaviest region of stress is displayed.
Decomposition Modeling / Cellular Decomposition

• Represent solid as a combination of *irregular cells* that are pasted together over common faces

Example: FEA

Here is an example of Finite Element Analysis used in *satellite imaging*. The colors show the activities of each cell.
The space subdivision method uses a recursive scheme to breakdown or **subdivide the solid**. The divisions are typically **rectangular blocks**. A good example of a model of this type is the **octree representation** where the solid is broken down into **8 subdivided blocks**. Each block of the octree is further subdivided into **8 blocks called octants** and so on as represented by the left picture in figure C. Each block has either one material type, no material, or is defined by smaller blocks.
All CAD solid modeling programs utilize *additive* and *subtractive* modeling methods to create virtual 3D objects. They are also referred to as *Boolean operations*, named after the 18th century English mathematician Charles Boole.

- Primitives can be used to build solid geometry with Boolean Operations

- **Union**: $A \cup B$
- **Difference**: $A - B$
- **Intersection**: $A \cap B$
Construction Solid Geometry (CSG) : Solid Primitives

Rectangular Prism
Triangular Prism
Cylinder
Sphere
Cone
Torus
Primitive Creation

- Primitives are simple solid shapes with simple mathematical surfaces.
- Can be controlled by a small number of parameters and positioned using a transformation matrix.

Diagram showing:
- Block
- Cylinder
- Cone
- Sphere
- Wedge
- Torus
Solid Model Operators:

- Subtract / Cut
- Intersection
- Union

- **Subtract**
  - subtracts one solid from another

- **Intersection**
  - Creates a solid that represents the region that is in common to the selected solids
- **Union**
  - Creates a single solid from two solids that intersect
Boolean Operations

- Boolean operations are used to make more complicated shapes by combining simpler shapes.
- 3 types of operations are possible:
  - union (‘∪’) or “join”
  - intersection (‘∩’)
  - difference (‘-’) or “subtract”
- Be careful:
Constructive Solid Geometry (CSG)

A lengthy, lousy process

(a) Construction tree
**Example:** Solid Model Operators

What procedure would you follow to create the two mating parts?

- Create the bounding box for the upper part
- Create the two cylinders
- Subtract the cylinders from the box
- Create the bounding box for the lower part
- Subtract the finished upper part
Additive Methods:
A three dimensional object can be viewed as the combination of two or more simple forms. In the creation of real world objects, this method is represented by construction processes such as welding, gluing, mechanical fastening, and joining.
Subtractive Methods:
An object can be viewed as the remainder of a solid block that has had the geometry of one or more forms sequentially removed.

In the creation of real world objects, this method is represented by *milling, drilling, turning, grinding*, and other manufacturing processes.
Combining the Methods:
Most objects can be modeled efficiently through the combination of both additive and subtractive methods.

There is no right or wrong way to generate a solid model. However, the process that uses the least number of steps in the shortest amount of time is the most efficient way.
Solid Modeling: Constructive solid Model: Boolean Operation
Example: Solid Modeling: Constructive solid Model: Boolean Operation

Object = (A - B) \cup (C - D)
Figure below shows Boolean operations of a block A and Cylinder B
Figure below shows Boolean operations of a block P and Solid Q

Union \((P \cup Q)\)

Difference \((Q - P)\)

Intersection \((P \cap Q)\)

Difference \((P - Q)\)
Data structures for the CSG representation are based on the binary tree structure. The CSG tree is a binary tree with leaf nodes as primitives and interior nodes as Boolean operations.
CSG Creation Process

The creation of a model in CSG can be simplified by the use of a table summarizing the operations to be performed. The following example illustrates the process of model creation used in the CSG representation.
<table>
<thead>
<tr>
<th>Primitive No.</th>
<th>Primitive Type</th>
<th>Transformations $S(x,y,z)$ $T(x,y,z)$ $R(x,y,z)$</th>
<th>Boolean $(U, D, I)$</th>
<th>CSG Tree</th>
<th>Sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Block</td>
<td>$S(3.0, 2.5, .62)$</td>
<td></td>
<td></td>
<td><img src="image" alt="Block Sketch" /></td>
</tr>
<tr>
<td>2/3</td>
<td>Block</td>
<td>$S(0.5, 2.0, .62)$ $T(2.5, 0.5, 0.0)$ $S(0.5, 2.0, .62)$ $T(0.0, 0.5, 0.0)$</td>
<td>D/D</td>
<td><img src="image" alt="Block Tree" /></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Cylinder</td>
<td>$S(r = 0.44, h = 0.62)$ $T(1.5, 1.5, 0.0)$</td>
<td>D</td>
<td><img src="image" alt="Cylinder Tree" /></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Block</td>
<td>$S(0.56, 0.12, 0.62)$ $T(1.94, 1.44, 0.0)$</td>
<td>D</td>
<td><img src="image" alt="Block Tree" /></td>
<td></td>
</tr>
<tr>
<td>6/7</td>
<td>Cylinder</td>
<td>$S(r = 0.125, h = 0.5)$ $T(0.25, 0.0, 0.31)$ $R(90.0, 0.0, 0.0, 0.0)$ $S$(same) $T(2.75, 0.0, 0.31)$ $R$(same)</td>
<td>D/D</td>
<td><img src="image" alt="Cylinder Tree" /></td>
<td></td>
</tr>
</tbody>
</table>
Boundary representation (B-rep) models

The de facto standard for CAD since ~1987
  BReps integrated into CAGD surfaces + analytic surfaces + boolean modeling
Models are defined by their boundaries
Topological and geometric integrity constraints are enforced for the boundaries
  Faces meet at shared edges, vertices are shared, etc.

BRep Data Structure

Vertex structure
  X,Y,Z point
  Pointers to \( n \) coincident edges

Edge structure
  2 pointers to end-point vertices
  2 pointers to adjacent faces
  Pointer to next edge
  Pointer to previous edge

Face structure
  Pointers to \( m \) edges

Winged-Edge Data Structure

Vertex
  \( n \) edges

Edge
  2 vertices
  2 faces

Face
  \( m \) edges
**Issues in Boundary Representation Solid Modeling**

- Very complex data structures
  - NURBS-based winged-edges, etc
- Complex algorithms
  - Manipulation, booleans, collision detection
- Robustness
- Integrity
- Translation
- Features
- Constraints and Parametrics

**Boundary Models:** Here a solid object is represented by dividing the surface into a collection of faces such that each face is easily described mathematically. Boundary modes are enclosed by a set of boundary surfaces enclosed by boundary curves. Most solid modeling packages use the boundary representation for storing the models. The solid is considered to be bounded by a set of faces. The faces have a compact mathematical representation as a plane, toroidal, cylinder or some parametric surface such as a Bezier surface.

**Information storage models:**
- Geometrical - Point coordinates, equations for edges and faces
- Topological - Edges bounding a face, which faces are adjacent

**STL files** have planar triangles as bounding surfaces

Many **solid modelers** store both **CSG** and **boundary representation** models
A general data structure for a boundary model should have both topological and geometrical information.

- **Geometry** relates to the information containing shape defining parameters, such as the coordinates of the vertices.

- **Topology** describes the connectivity among the various geometric components, that is, the relational information between the different parts of an object.
B-Rep data structure

B-Rep graph store face, edge and vertices as nodes, with pointers, or branches between the nodes to indicate connectivity.

Combinatorial structure / topology

Metric information/ geometry
Same geometry but **different topology**

Same topology but **different geometry**
B-Rep Entities Definition

- **Vertex** is a unique point in space
- **An Edge** is a finite, non-self-intersecting, directed space curve bounded by two vertices
- **A Face** is defined as a finite connected, non-self-intersecting, region of a closed oriented surface bounded by one or more loops
• **A Loop** is an ordered alternating sequence of vertices and edges. A loop defines a non-self-intersecting, piecewise, closed space curve which, in turn, may be a boundary of a face.

• **A Handle (Genus or Through hole)** is defined as a passageway that passes through the object completely.

• **A Body (Shell)** is a set of faces that bound a single connected closed volume. Thus a body is an entity that has faces, edges, and vertices.
To ensure topological validation of the boundary model, special operators are used to create and manipulate the topological entities. These are called Euler Operators.

The Euler’s Law gives a quantitative relationship among faces, edges, vertices, loops, bodies or genus in solids:

\[
F - E + V - L = 2(B - G)
\]

**Euler Law**

**Where**

- \(F\) = number of faces
- \(E\) = number of edges
- \(V\) = number of vertices
- \(L\) = Faces inner loops
- \(B\) = number of bodies
- \(G\) = number of genus (handles, torus, through hole)
\[ F - E + V - L = 2(B - G) \]
\[ [14 - 36 + 24 - 2 = 2(1 - 1)] \]

\[ F - L + V = 2 \]
\[ (10 - 24 + 16 = 2) \]

\[ F - L + V = 2 \]
\[ (6 - 12 + 8 = 2) \]
Solids that have a uniform thickness in a particular direction and axisymmetric solids can be created by what is called Transitional (Extrusion) and Rotational (Revolution) Sweeping.

Sweeping requires two elements — a surface (generator) to be moved and a trajectory, analytically defined, along which the movement should occur.

Many manufacturing processes (milling, turning, ...) can be directly modeled as sweep operations.
Feature-Based Modeling

- Features are shapes having *engineering significance*. They usually are the geometric embodiment of *machining operations* or the *function* of a component.
- Examples:
  - hole - pocket
  - slot - boss
- Many people use the term “Feature” to refer to any kind of solid modeling operation.
- Many systems provide for user-defined features.
Feature based Solid Modeling

• Parts modeled by adding **features** to a base part
• Features represent “operations”
  • holes, ribs, fillets, chamfers, slots, pockets, etc.
• Material can be added or subtracted
• Features can be created by extrusion, sweeping, revolving, etc.

Feature-based Modeling Process

- Create base part
- Add features until final shape is achieved
Feature History Trees

- Most feature-based modelers show the features and their order in a graphical tree view

Modifying Parts

- The part is created from the history tree
- Features can be added, deleted and re-ordered
- Feature parameters can be changed
Feature-based models

- geometric models are a limited representation of reality

→ features
  - nominal geometry
  - tolerance
  - assembly
    - mating conditions, relative position and orientation, fits
    - kinematic relations
  - funcional
  - material
    - material composition, treatments, etc.
Common elements of a solid parametric feature-based CAD system

1. Sketching Environment
2. Features
   - Extrusion
   - Revolution
   - Sweep
   - Blend (or loft)
   - Round (or Fillet)
   - Chamfer
   - Hole
3. Model Tree
4. Intelligent Features (Parameters)
5. Ease of Modification
6. Integration/Associativity
7. Design Intent
8. Datum/Reference Planes
SolidWorks

Feature Manager Design Tree
CAD standards

With the proliferation of the computers and software in the market, it is necessary to standardize certain elements at each stage, so that the files and the data will not be lost or used with much modification in the newer and different systems.

This means there should be compatible between various software elements as also between the hardware and software.

This can be achieved by maintaining proper interface standards at various levels.

Following are some of the standards: GKS、IGES、DXF、STEP ……

Exchange of modeling data

Since the CAD/CAM software is available from a number of vendors, it is necessary to communicate with the various systems in the same plant or different plants. This means that the data format used by all the software should be the same. The database formats are identified on the basis of the modeling requirements and it is not possible to have identical format for all the systems. But it is possible to identify a certain format for drawing exchange and make it a standard so that the various systems can convert their internal format to this format.
IGES (Initial graphics exchange specification)

The IGES is the most comprehensive standard and is designed to transmit the entire product definition including that of manufacturing and any associated information.

The IGES file consists of 6 sub-sections:
- Flag section: indicate the form which the data is specified in.
- Start section: a man-readable prologue
- Global section: details of the product, person and company, the system, drafting standard used, some information required for its post processing.
- Directory entry section: provide an index for the file an contain attribute information such as colour, line type, transformation matrix, etc.
- Parameter data section: contain the data associated with the entities.
- Terminate section: contain the sub-totals of the records present in each of earlier sections.

All kinds of modeling (wire modeling, surface modeling, solid modeling) information can be convenient handled in IGES.

Some problems should be faced with IGES for translation of geometry between different systems.

Some problems should be faced with IGES because of the following reasons:
- The different export choice for exporting CAD geometric data through IGES can make the result better or worse.
- The different system has accuracy or resolution. The IGES files are moved between two CAD/CAM products using different tolerance. Solid modeling is more sensitive than surface modeling because of this data problem.
- The translation time is too long.
STEP (Standard for exchange of product model data)

It is a series of international standards with the goal of defining data across the full engineering and manufacturing life circle. The broad scope of STEP is as follows:

- The standard method of representing the information necessary for completely defining a product through their entire life from concept design to the end of useful life.
- Standard methods for exchanging the data between two different systems.

The STEP file consists of 8 major areas:

- Overview
- Description methods
- Implementation methods
- Conformance and tools
- Integrated-generic resources
- Application information models
- Application protocols
- Application interpreted constructs

Application protocols are the main protocols to be used as subsets of STEP information model for exchange of data between specific application systems (such as between two finite element systems or between a CAD and Process Planning system).

These parts describe not only what data is to be used to describe a product, but also how the data is used in the model.

DXF (Drawing exchange format)

It is a CAD data file format developed by Autodesk for enabling data interoperability between AutoCAD and other programs.

A drawing interchange file is simply an ASCII text file with a file extension of .DXF.

The overall organization of a DXF file is as follows:
- Header section
- Classes section
- Tables section
- Blocks section
- Entities section
- Objects section
Integrated CAD/CAE/CAM Systems

- Professional CAD/CAE/CAM Tools
  - CATIA (Dassault Systemes - IBM)
  - Unigraphics NX (Electronic Data Systems Corp - EDS)
  - I-DEAS (EDS)
  - Pro/ENGINEER (PTC)

- Other CAD and Graphics Packages
  - AutoCAD Mechanical Desktop
  - SolidWorks (CATIA)
  - Solid Edge (EDS)
  - MicroStation
  - Intergraph
**Integrated CAD/CAE Tools**

- **ANSYS** (from ANSYS Inc.)  
  - A growth leader in CAE and integrated design analysis and optimization (DAO) software
  - Covering solid mechanics, kinematics, dynamics, and multi-physics (CFD, EMAG, HT, Acoustics)
  - Interfacing with key CAD systems

- **NASTRAN** (from MacNeal-Schwendler)  
  - A powerful structural analysis program for analyzing stress, vibration, dynamic, nonlinear and heat transfer characteristics.
  - PATRAN provides an open flexible MCAE environment for multidisciplinary design analysis, and simulates product performance and manufacturing processes.

- **Pro/MECHANICA** (integrated with Pro/E)  
  [www.ptc.com](http://www.ptc.com)
  - A system provides an open flexible MCAE environment for multidisciplinary design analysis, and simulate product performance and manufacturing processes.
Integrated CAD/CAM Tools

- **Mastercam** (from CNC Software, Inc.)
  - A system for generating 2- through 5- axis milling, turning, wire EDM, lasers, mold base development and 3D design and drafting.
- **Virtual Gibbs** (from Gibbs and Associates) [www.gibbscam.com/](http://www.gibbscam.com/)
  - A powerful, full featured CAM system for NC programming
- **Pro/MANUFACTURING** (integrated with Pro/E)
  - A system for generating machine code (CNC codes for 3 axis milling, turning and wire EDM) to produce parts.
- **SURFCAM** (from Surfware Inc. CA) [http://www.surfware.com/](http://www.surfware.com/)
  - An outgrowth of the Diehl family’s machine shop
  - A system for generating 2~5- axis milling, turning, drilling, and wire EDM.
  - Toolpath verification (MachineWorks Ltd.)
- **Rhinoceros** (NURBS modeling) [www.rhino3d.com/](http://www.rhino3d.com/)
  - Industrial, marine, and jewelry designs; cad/cam; rapid prototyping; and reverse engineering
Tools Commonly Used in Computer Aided Design

- Representing geometric shape
  - Computer graphics (2D)
  - Geometric modeling (3D)
- Interactive Graphical Programming
  - Programming on different platforms
  - Graphical User Interface
- Manipulating and storing design data
  - Data structure design
  - Database system
- Generating feasible designs (automatically)
  - Knowledge reasoning
  - Knowledge-based system
  - Fuzzy logic
  - Artificial neural networks
- Evaluating design alternatives and identifying the optimal solution
  - Numerical optimization
  - Finite elements method
  - Cost modeling and analysis