Chapter 6:
Computer Aided Manufacturing

Ramy Harik

Director, Clemson Composites Center

Professor, School of Mechanical and Automotive Engineering

ExxonMobil Employees Endowed Chair

harik@clemson.edu

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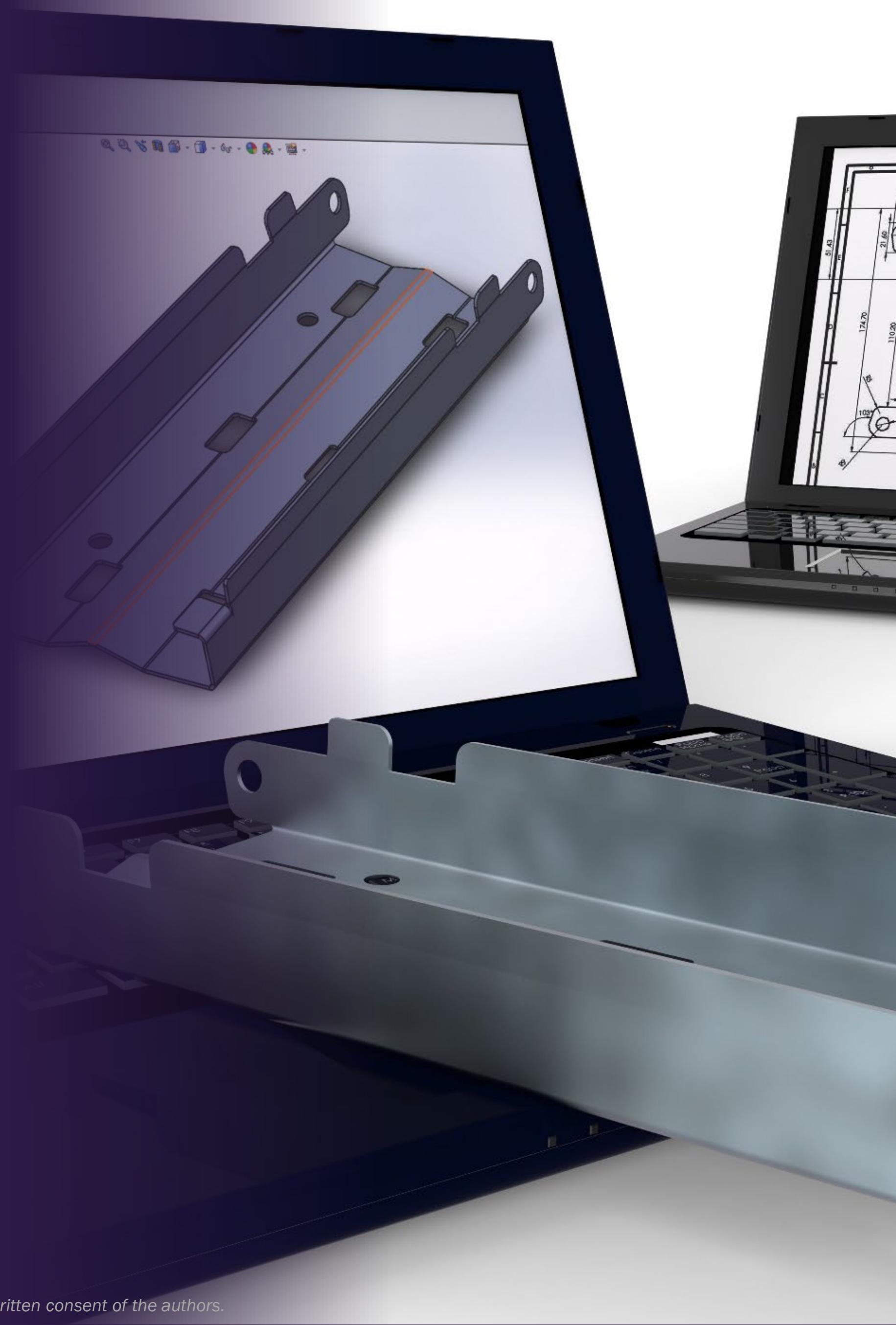


Outline

CAx

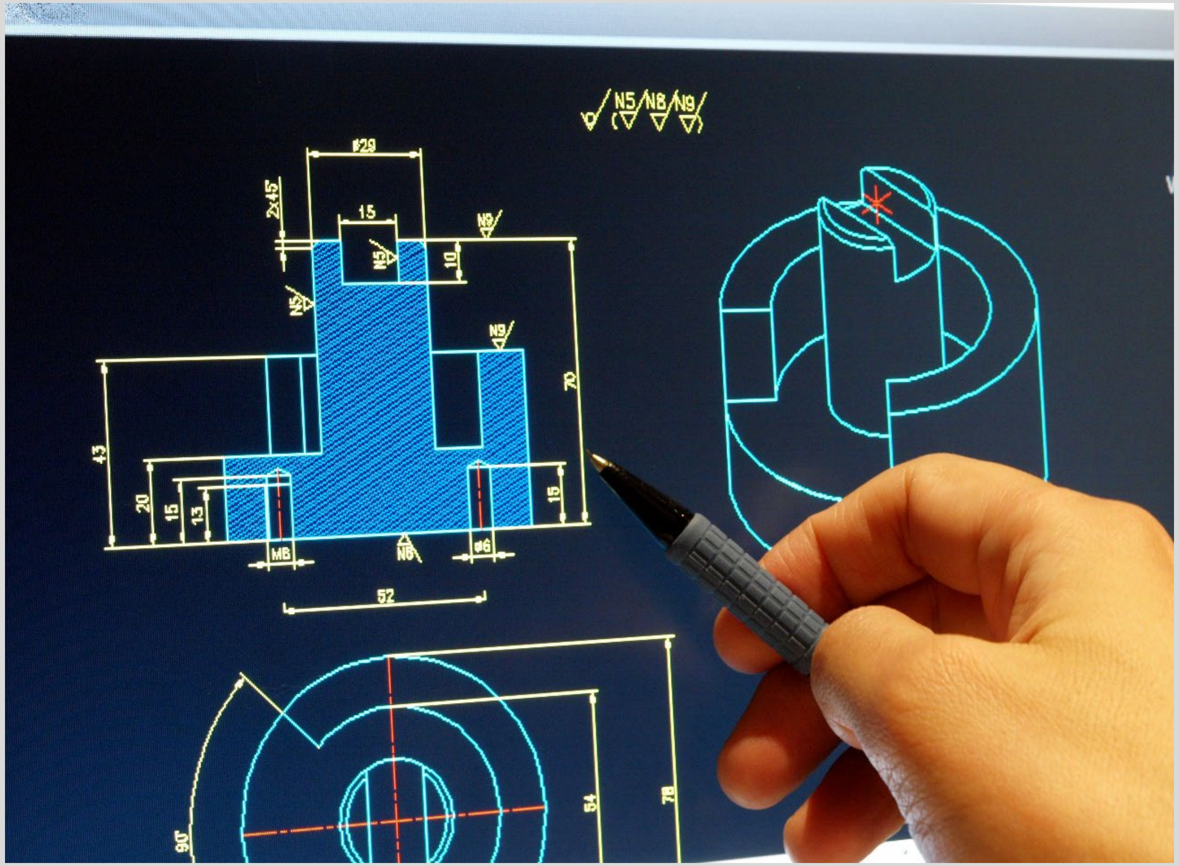
- CAx stands for **Computer-Aided X**, where x can be:

- D = Design

- M = Manufacturing

- PP = Process Planning

- E = Engineering



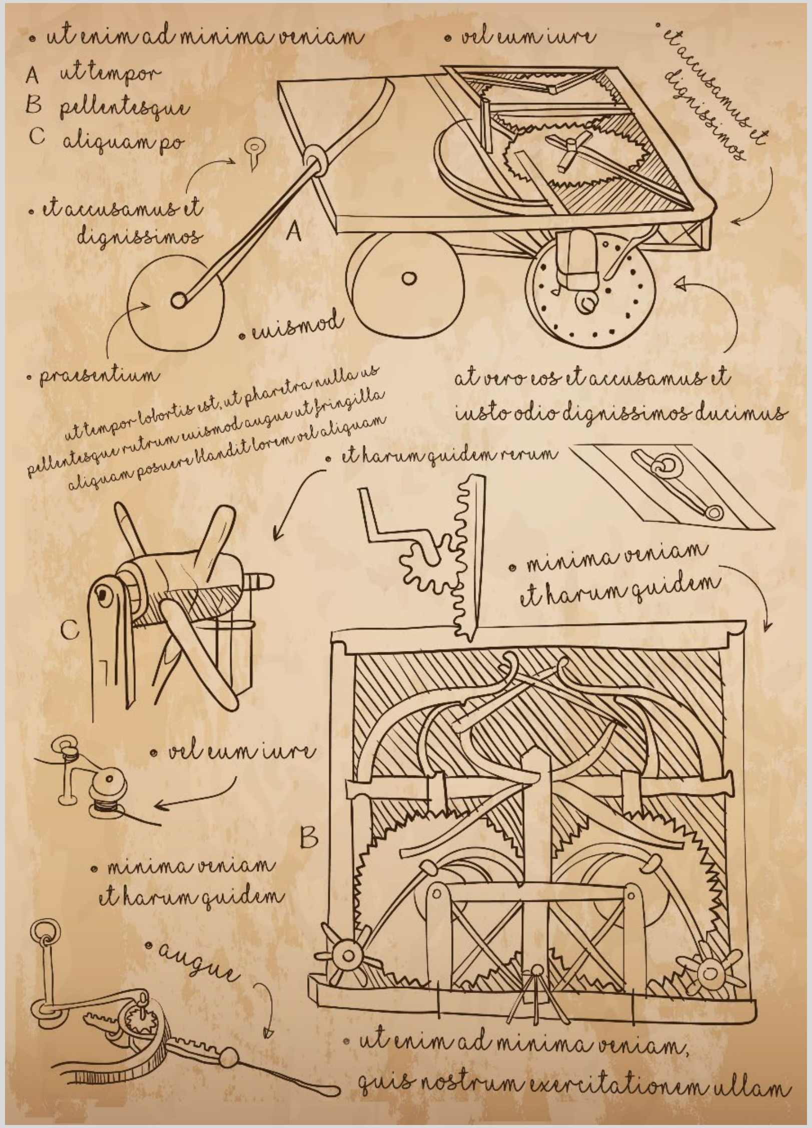
From Hand Drawing to … Product Lifecycle Management

- **Hand Drawing**
  - Started as an archival process for data perpetuation
  - There is room for interpretation - those who made the drawing might be the only one understanding it
  - Changing the design requires new drawings
  - Not easy task for Complex 3D Shapes
- **Computerized 2D/3D Modeling**
  - Modeling lacks documentation on relevant information such as materials and specifications
  - Not parametric
  - change management not optimized
- **Digital Mock-up (DMU)**
  - Enables collaboration and starts managing functionality
  - Replaces the PMU (Physical Mock up) and reduces creation lifecycle (example automotive sector: 4 years to 1.5 years)
- **Product Lifecycle Management (PLM)**
  - Offers interoperability management across trades
  - Manages product data, functions and resources across the BOL, MOL and EOL (Beginning/Middle/End of Life)

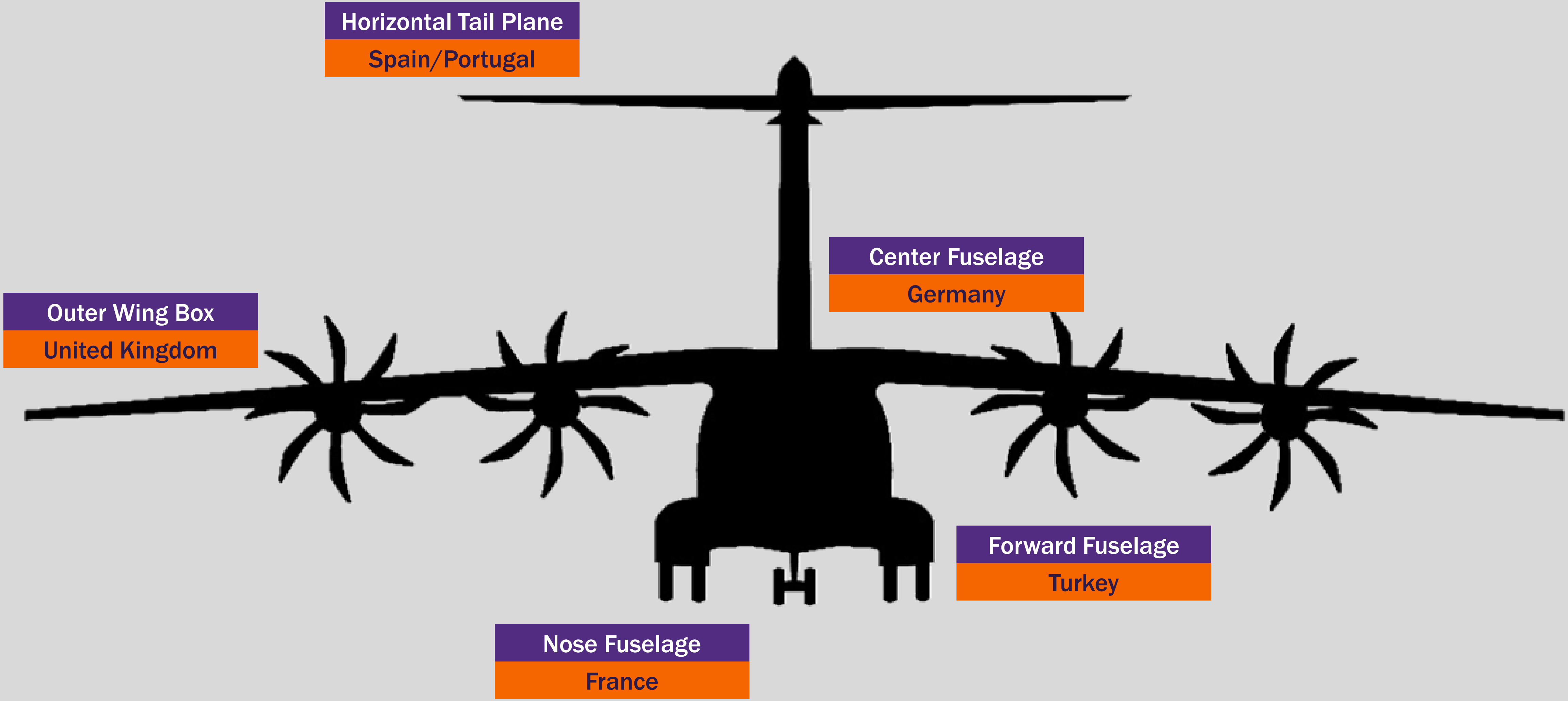
Hand drawing → Computerized 2D → 3D Modeling → DMU → PLM

Complexity of Hand Drawn Designs

- Da Vinci's "Automobile", the self-propelled car, was designed in 1478
- Da Vinci's design was complex, and it was hard to 'translate' his intentions and understand the functionality
- It is often considered as the 'first car'
- The first prototype based on Da Vinci's original design was manufactured in 2004



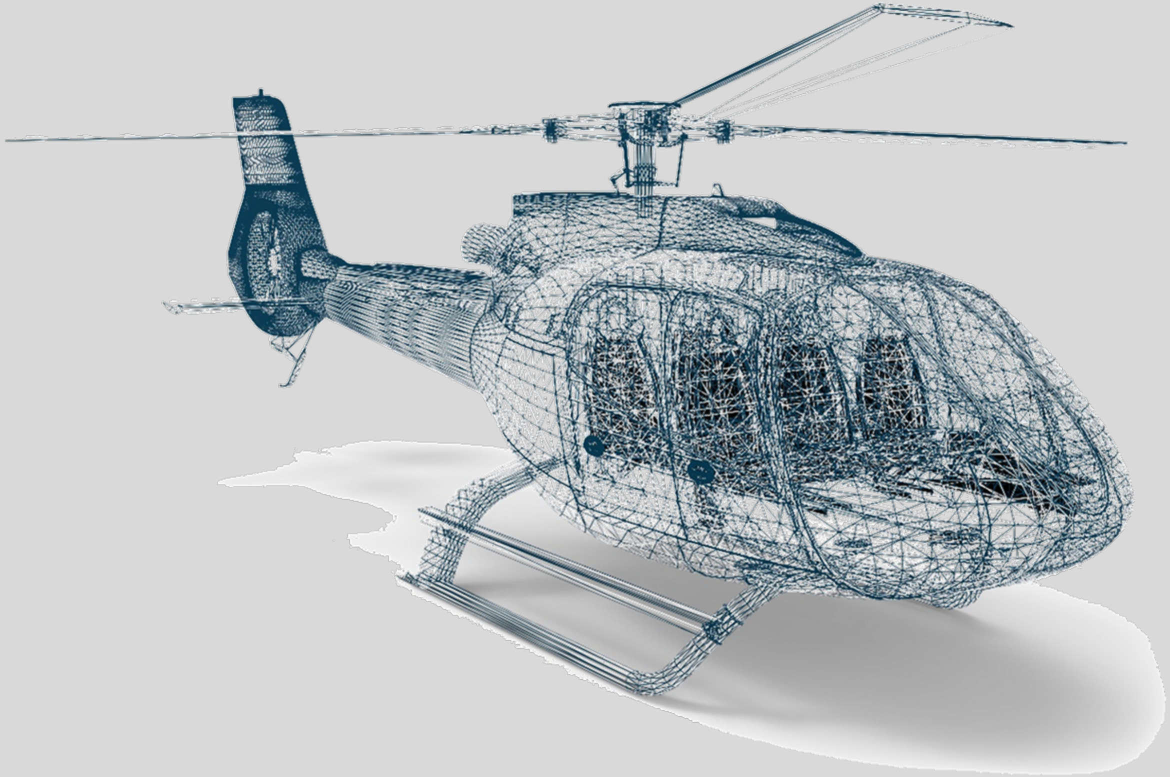
Today's World: Concurrent/Collaborative Engineering



Simple vs Complex Design

Direct Use of CAD System

Requires PMU/DMU



When to Use CAM Systems?

Advantages

- **Process reliability:** Ability to obtain the same result based on the same conditions
- **Accuracy:** Overcomes manual operation errors induced by human factor
- **Communication:** Enable cross-cultural communication as the machine communication platforms are ISO standards (G-Code)

Disadvantages

- **Expertise required:** Programmers are hard to acquire and train
- **Multiple platforms:** There exist multiple programming platforms making the training process tool specific
- **Expensive:** Some specific tools (such as for Automated Fiber Placement) are expensive and require a major investment
- **Post Processing:** Requires further understanding to obtain machine files

Knowledge Check

What is CAM

A. Computer Aided Machining
B. Computer Aided Manufacturing
C. Computer Assisted Manufacturing

Knowledge Check

What is CAM

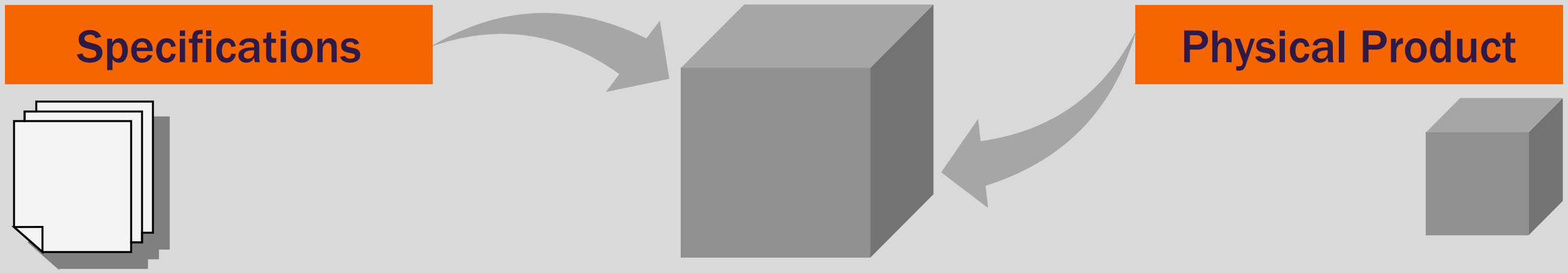
A. Computer Aided Machining
B. **Computer Aided Manufacturing**
C. Computer Assisted Manufacturing

The Numerical Chain

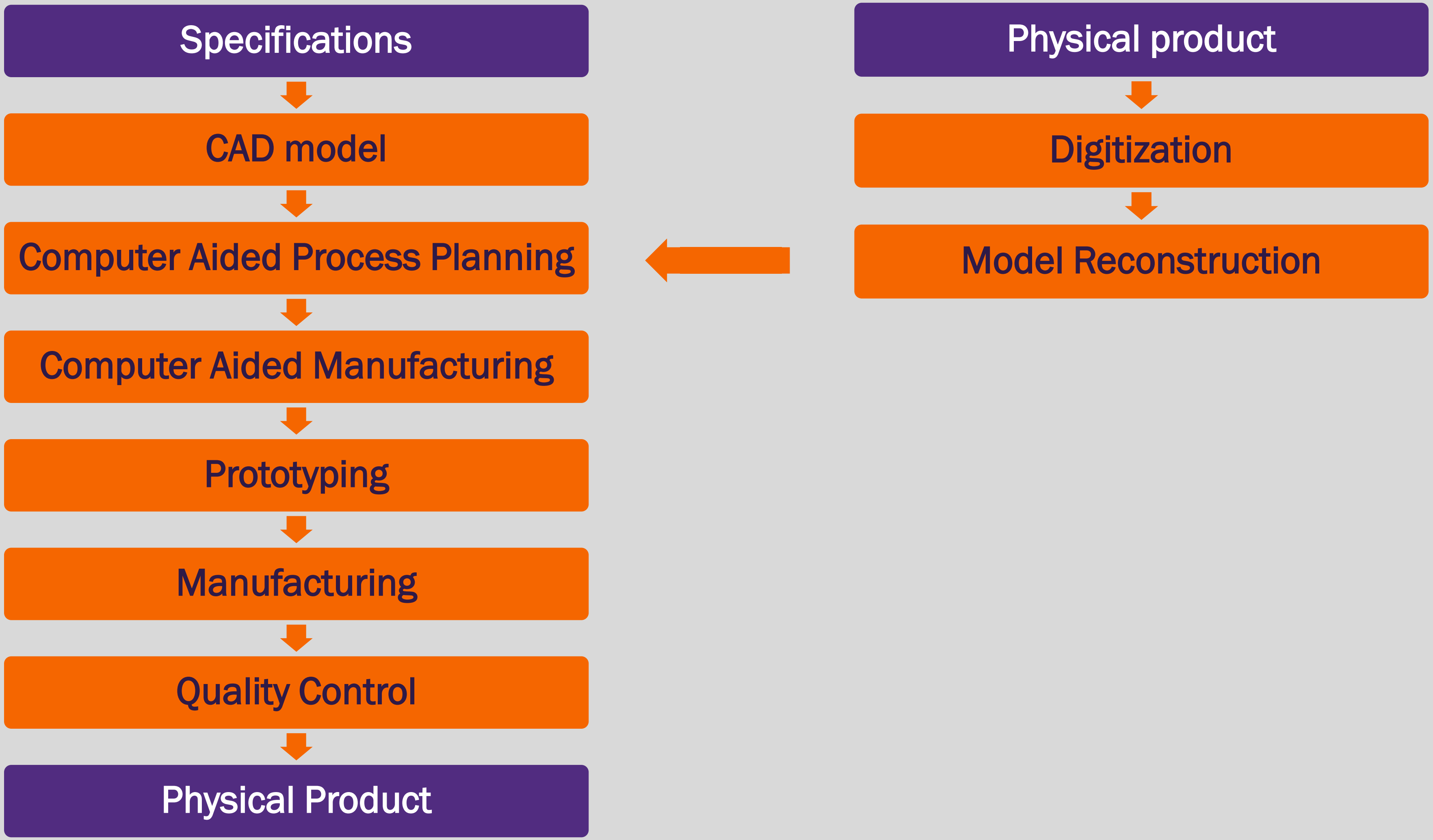
Section I

Complexity of Hand Drawn Designs

- The numerical chain supports the generation of a new product across several trades
- We replace the physical chain by numerical computations and simulations
- A direct result of the numerical chain application is a reduction of errors and time-to-market for new products
- The numerical chain encompasses the product modeling, geometrical modeling, manufacturing as well as other attributes
- We often distinguish two numerical chains, based on the initial starting point:
    - Specifications
    - Physical Product



The Numerical Chain



I.A | Specifications

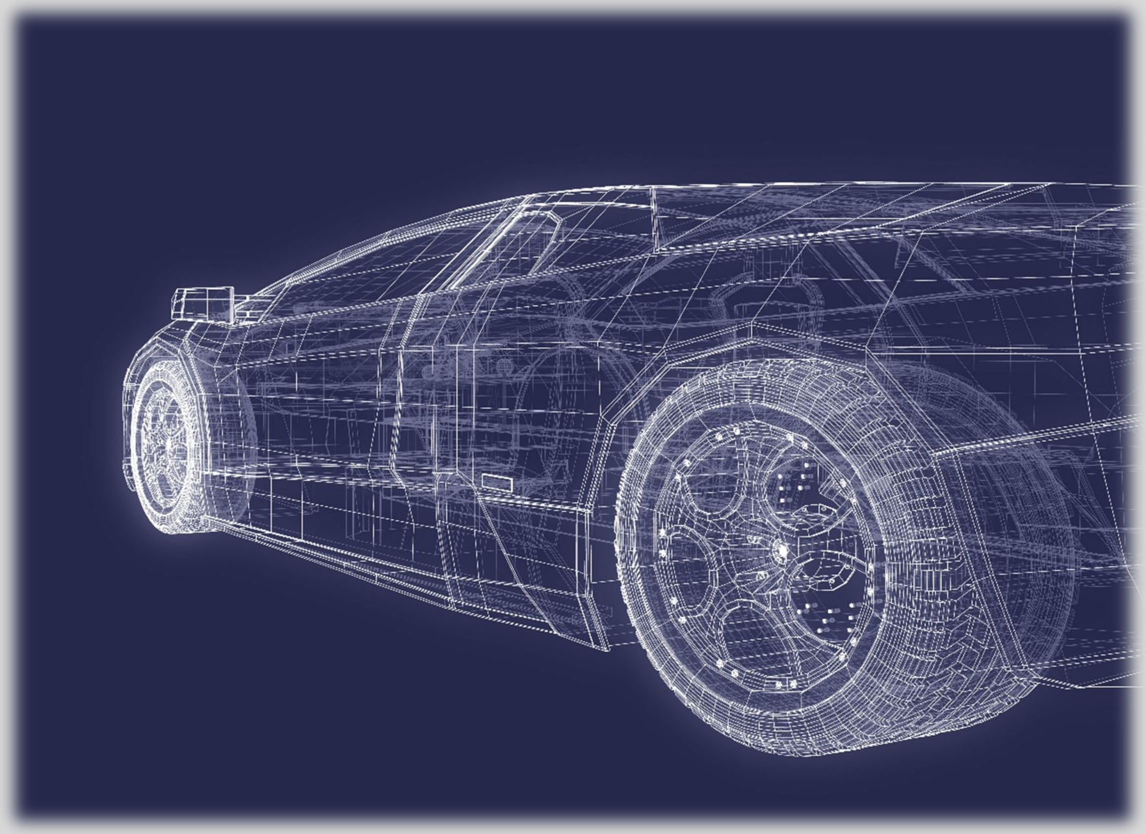
- The starting point for any project are the user requirements
- This include functional behavior and expected performance indicators
- With the dawn of IoT & PLM, there is a trend to use sensors to inform design specifications and derive requirements
- Poor specifications can lead to a non-conform design & unsatisfied customers
- Generally, in design, it includes bounding volume and mating surfaces for assembly
- Material specification can be provided or can be selected during the design process

Word Document

I.B | Computer Aided Design

- Computer Aided Design (CAD) started as a computer graphics initiative to create 2D drawings
- Ivan Sutherland is often regarded as the founder of CAD with his Sketchpad software while at MIT in 1963
- Today's CAD systems are often referred to as PLM (Product Lifecycle Management) solutions
- Three major companies dominate the CAD market: PTC Creo, Dassault Catia and Siemens NX.

CAD Model



I.C | Digitization

- A major step in 'Reverse Engineering' where we acquire **cloud of points** that represents the design

- Often a model reconstruction step is needed following the 3D scanning process

- There exist a variety of **mechanical and optical systems** to capture model geometry

- Recent advances enable **material recognition** as part of the scanning process

- Digitization typically requires treatment and processing of the cloud of points

Cloud of Points

I.D | Model Reconstruction

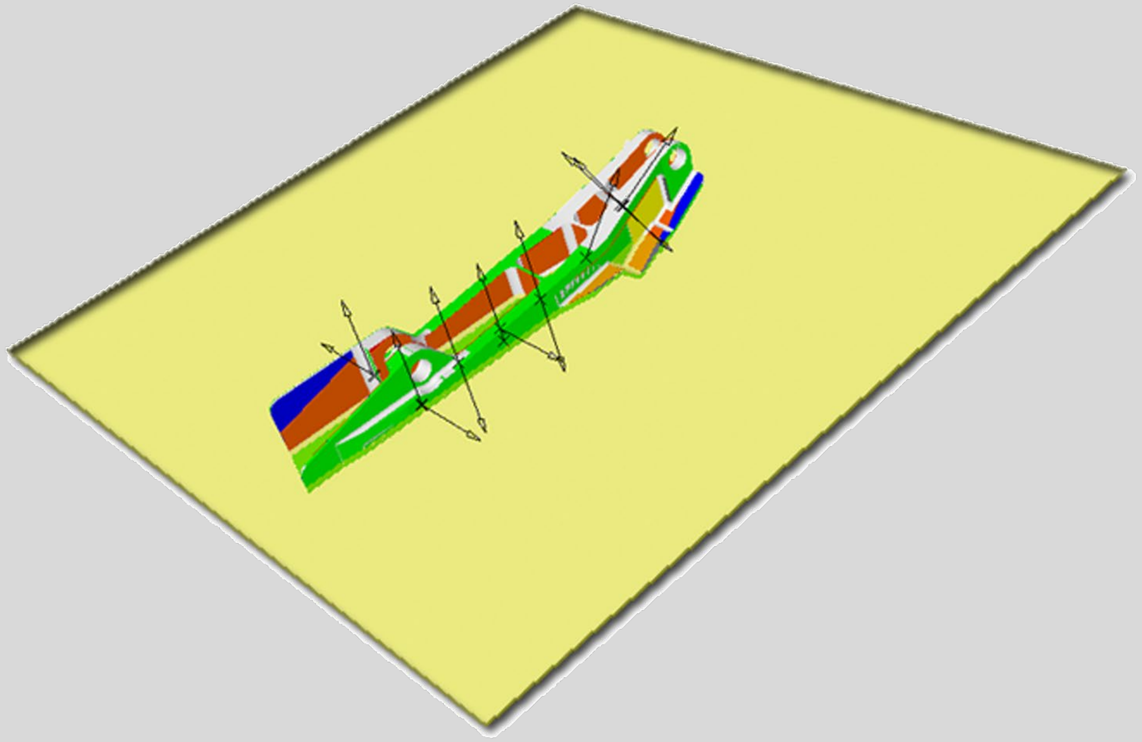
- Model reconstruction targets fusion of cloud of points (COP) received by digitization step
- Multiple automated referencing systems support unification of COP
- COP requires further treatment to remove ‘’noises’’ and undesired points acquired
- COP is then used to recreate a boundary representation of the model including a topological hierarchy

CAD Model

I.E | Computer Aided Process Planning

- The process planner has a reconciliatory role: matching the design with the manufacturing resources.
- It requires human analysis of the mechanical part, which is often complex and time-consuming.
- Neglected machining difficulties or un-noticed ones, have detrimental consequences on meeting the allowable specified by the part designers.

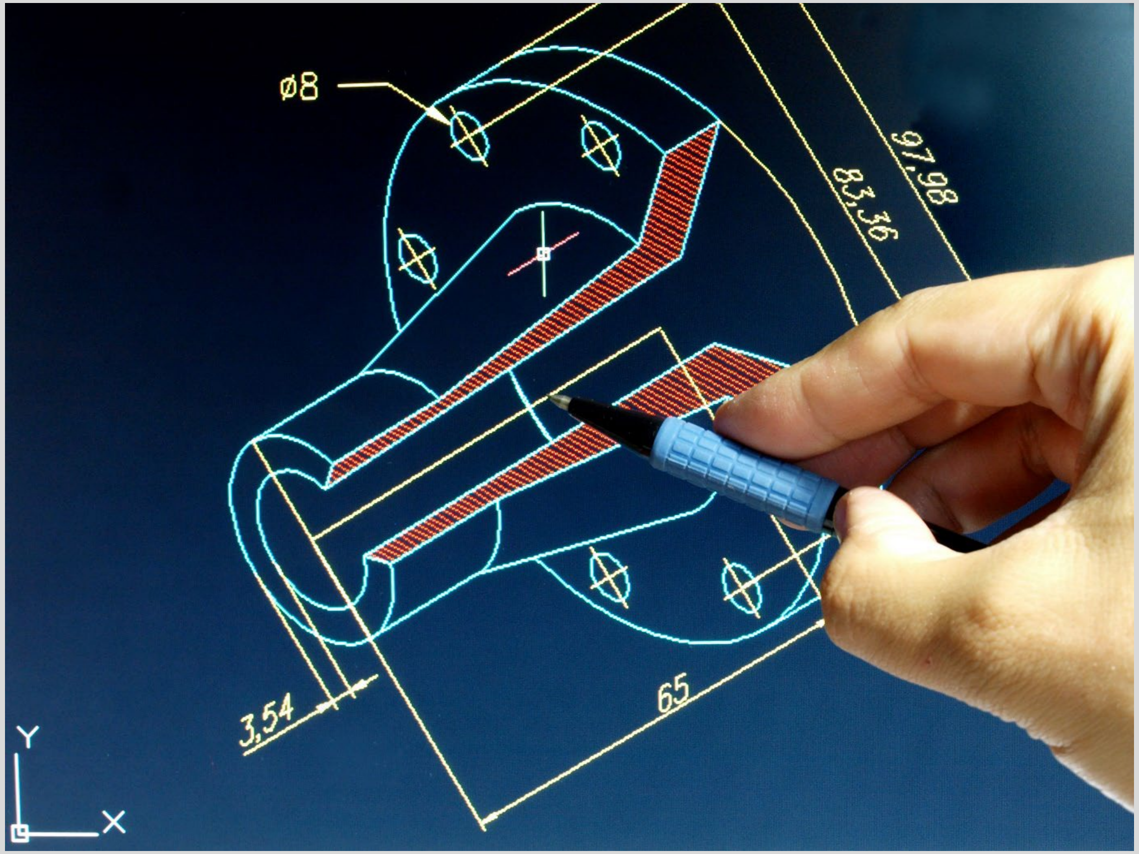
Process Plan



I.F | Computer Aided Manufacturing

- Translation of the process plan and process parameters into toolpath trajectories
- Selection of optimal toolpath plans that minimize both manufacturing defects and production time
- Often requires post processing to translate an APT file to NC Commands
- This step generates the files that are sent to the machine / manufacturing equipment

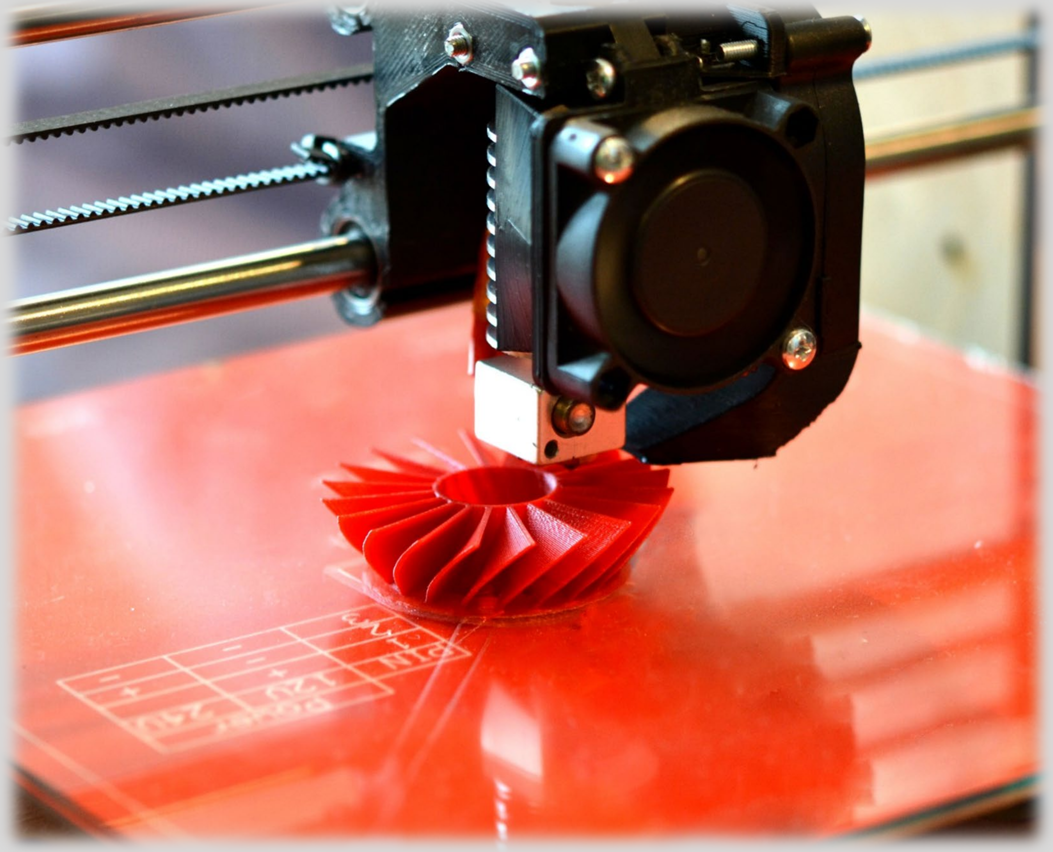
Toolpath Trajectory



I.G | Prototyping

- Prototyping describes an initial, small-scale/ on-of-a-kind manufacturing of the designed shape
- Often in a low-cost material and with reduced tolerances to verify general functionality
- Sometimes used as a preliminary step before proceeding with mass production
- Currently 3D printing is a preferred prototyping methodology

Low-cost prototype



I.H | Manufacturing

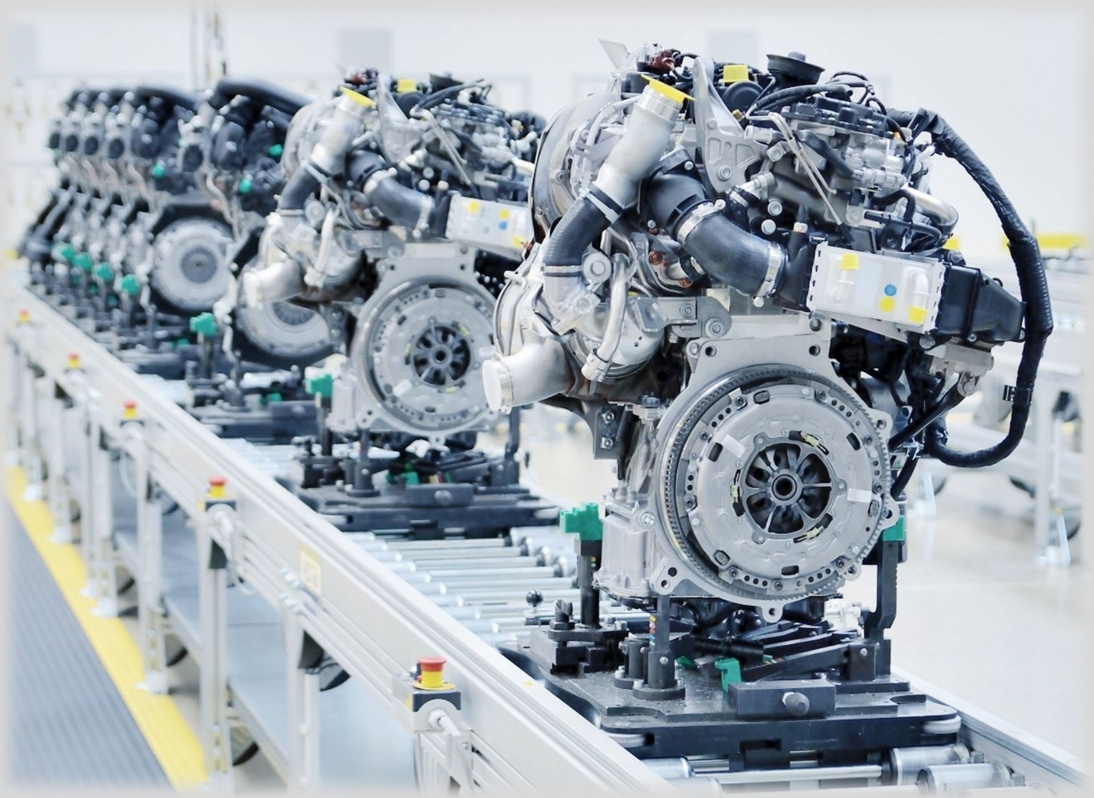
- Using the right material/tools (manufacturing resources), in this step we manufacture the physical product(s)

- It often involves reservation of resources and usage of production systems

- Most common variations of production systems' organization are push and pull systems

- Production management is conducted with ERP (Enterprise Resource Planning)

Physical Model



I.I | Quality Control

- Inspection process to ensure quality of manufactured goods
- Multiple methodologies are employed, such as sampling (in case of mass production) or individual control of each part (in-situ / ex-situ; destructive / non-destructive)
- Usage of statistical quality tools such as control charts and 80-20 to classify origins of defects and inaccuracies
- Zero defect policy is adopted in many innovative manufacturing environments

Inspection Report

Knowledge Check

How Many Numerical Chains There is?

A. One
B. Two
C. Three

Knowledge Check

How Many Numerical Chains There is?

A. One
B. **Two**
C. Three

Starting from (I) Specifications and (II) Physical Product

Knowledge Check

Model Reconstruction Results in…

A. Cloud of Points
B. CAD Model
C. Manufacturing Plan

Knowledge Check

Model Reconstruction Results in…

A. Cloud of Points
B. **CAD Model**
C. Manufacturing Plan

Knowledge Check

Prototyping is…

A. Creating a CAD model to facilitate production of physical parts
B. Inspection of how accurate the manufacturing process is and how many defects were present
C. Manufacturing the intended part, however with low-cost material

Knowledge Check

Prototyping is…

A. Creating a CAD model to facilitate production of physical parts
B. Inspection of how accurate the manufacturing process is and how many defects were present
C. **Manufacturing the intended part, however with low-cost material**

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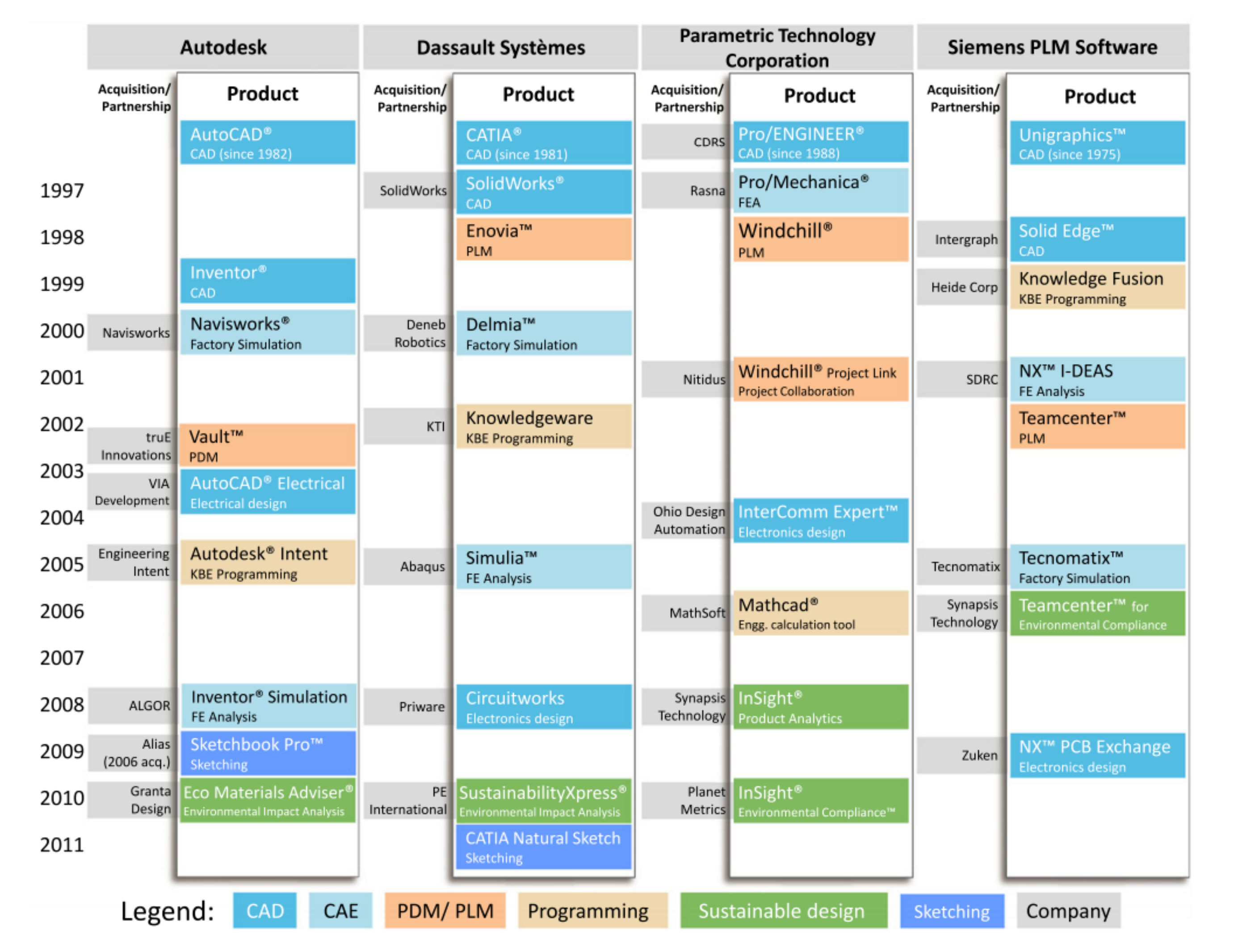
Geometrical Modeling

Section II

II.A | Big Three + Autodesk



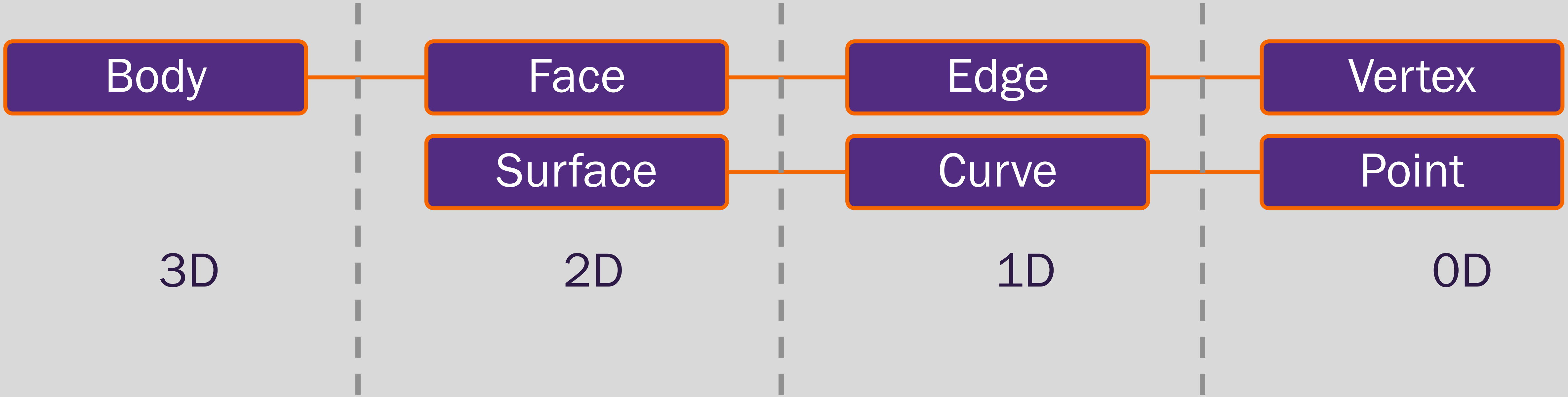
Topology vs Geometry

- All solid models have both geometry and topology components.
- Geometrical elements are ‘endless’ without boundaries. They define the underlying geometrical equations that generate the form.
- Topological elements are the connectivity between the multiple entities within the model.
- Both Topological and Geometrical elements are defined by their dimension (3D, 2D, 1D, 0D)
- Geometry has surfaces (2D), curves (1D) and points (0D)
- Topology has faces (2D), edges (1D) and vertices (0D)
- There exists a relationship between topology and geometry:

A topological element of dimension N, is a geometrical element of dimension N, bound by topological elements of dimension N-1.

- Example: A face is a surface bound by edges.

Topology vs Geometry



Knowledge Check

A Surface is a...

A. Geometrical Element
B. Topological Element

Knowledge Check

A Surface is a…

A. Geometrical Element
B. Topological Element

Knowledge Check

An Edge is…

A. A topological element with an underlying geometry represented by a curve, bounded by two vertices
B. A geometrical element bounded by two points

Knowledge Check

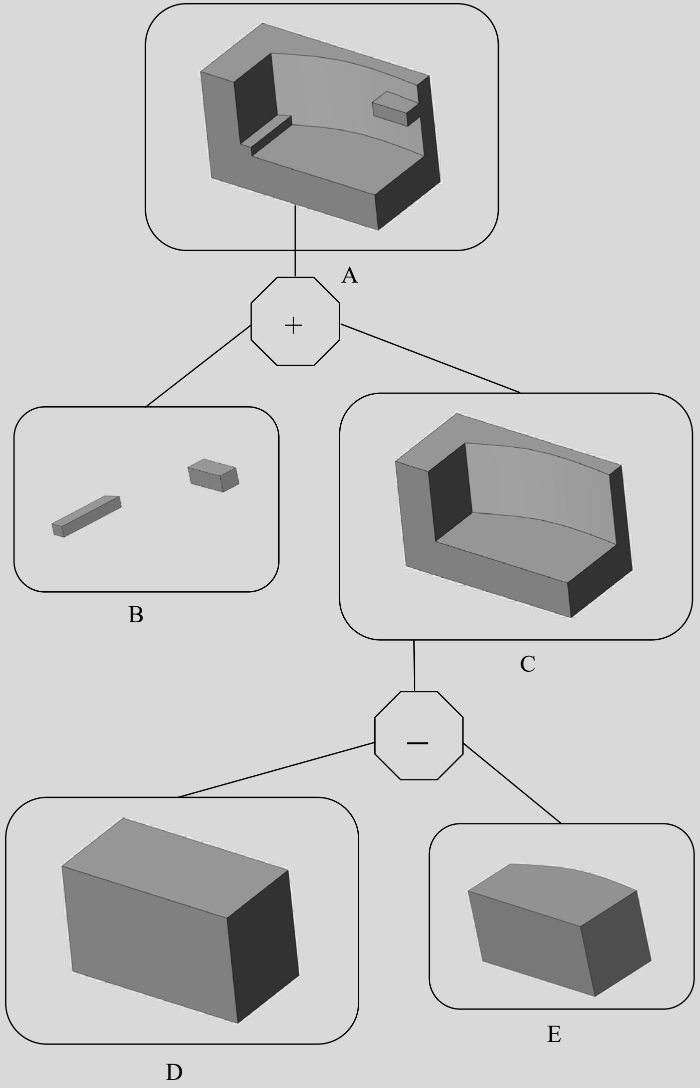
An Edge is…

A. A topological element with an underlying geometry represented by a curve, bounded by two vertices

B. A geometrical element bounded by two points

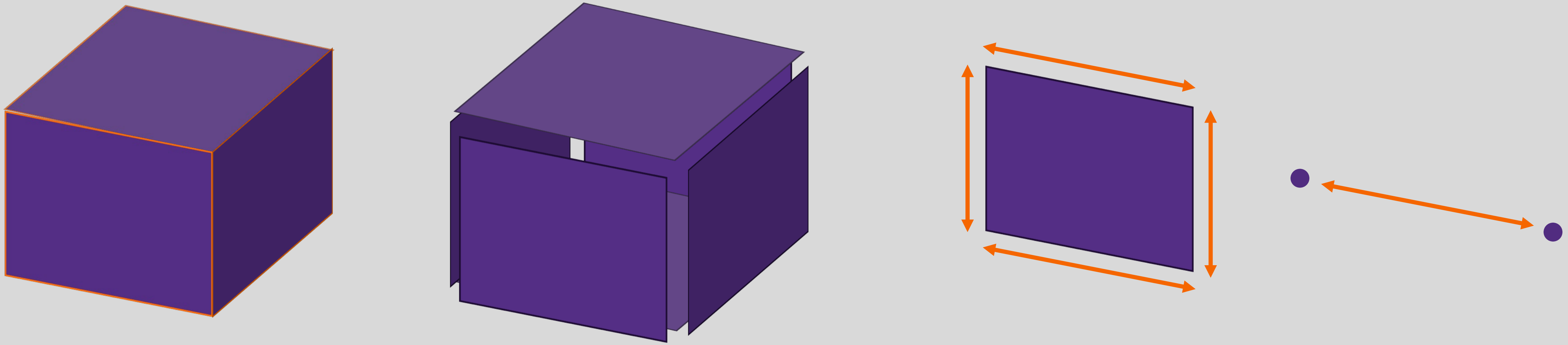
II.B | Constructive Solid Geometry

- Geometry is created through usage of Boolean operations on primitive geometrical shapes
- Typical Boolean operations are Intersection, Union, Subtraction, Complementation, Exclusive Union
- The model stores both the final topology and geometry of the model
- Typically present itself in a design tree



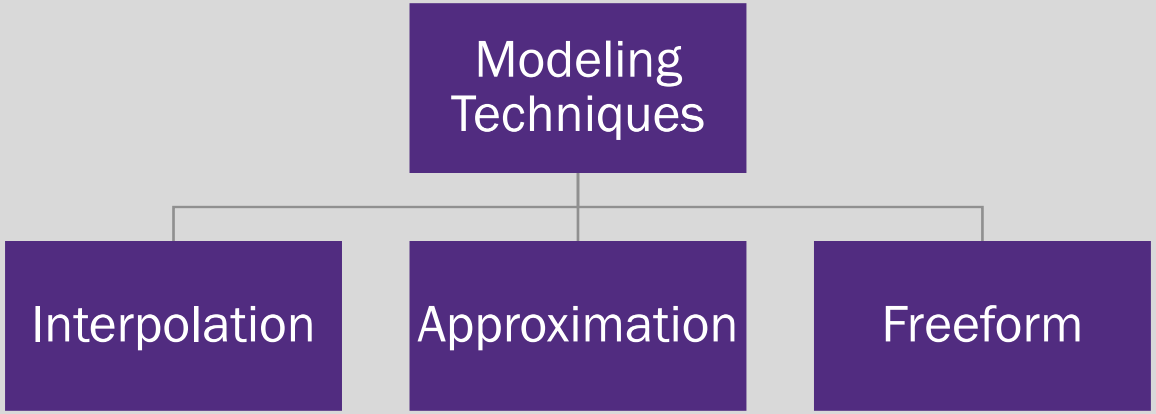
II.B | Boundary Representation B-Rep

- **B-Rep** or Boundary representation is the most common mode of presenting objects
- Models consists of faces, edges, vertices, loops and handles
- While faces, edges and vertices are the standard topological components, a loop is a hole in a face, and the handle is a through hole in a solid body



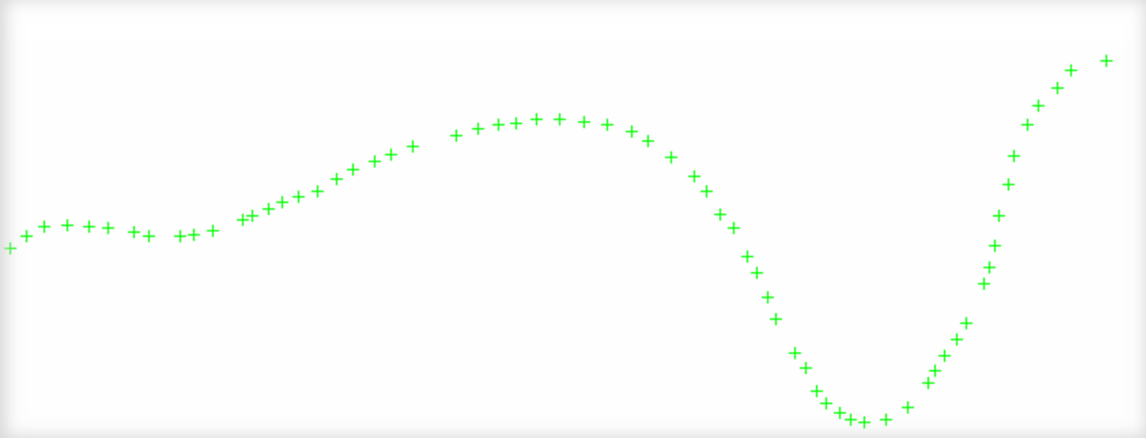
II.C | Modeling

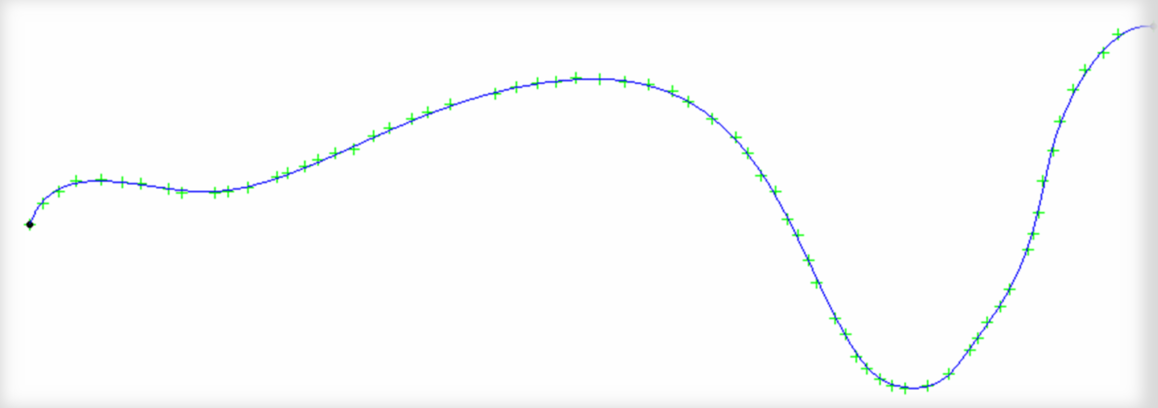
- Modeling of **Curves and Surfaces** is precursor to define and determine the overarching model
- The representation of curves and surfaces enables us not only to see the components, but also to **evaluate and manufacture** them
- Geometric representation can be:
  - Explicit □ $y = f(x)$
  - Implicit □ $f(x, y) = 0$
  - Parametric □ $x = f(t), y = f(t)$
- **Parametric** is the most suitable for manufacturing



II.C | Modeling: Interpolation

- Polynomial passes **through the given points**
- Degree is often of high order (Lagrange) or requires decomposition of model into multiple functions (Spline)
- The result is often not smooth but rather **oscillating** between points
- Spline method originates from naval construction techniques and is more accurate than Lagrange since it uses more than one polynomial to interpolate the points





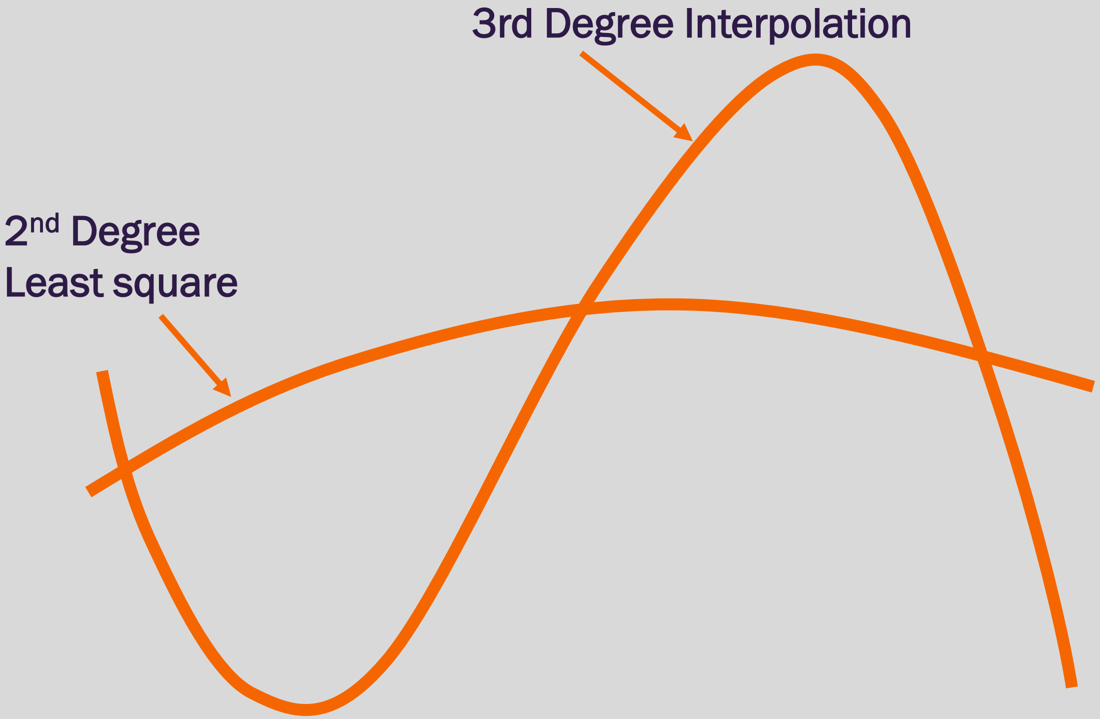
II.C | Modeling: Interpolation

- Polynomial passes **near the given points**

- Designer selects the degree of the approximation model

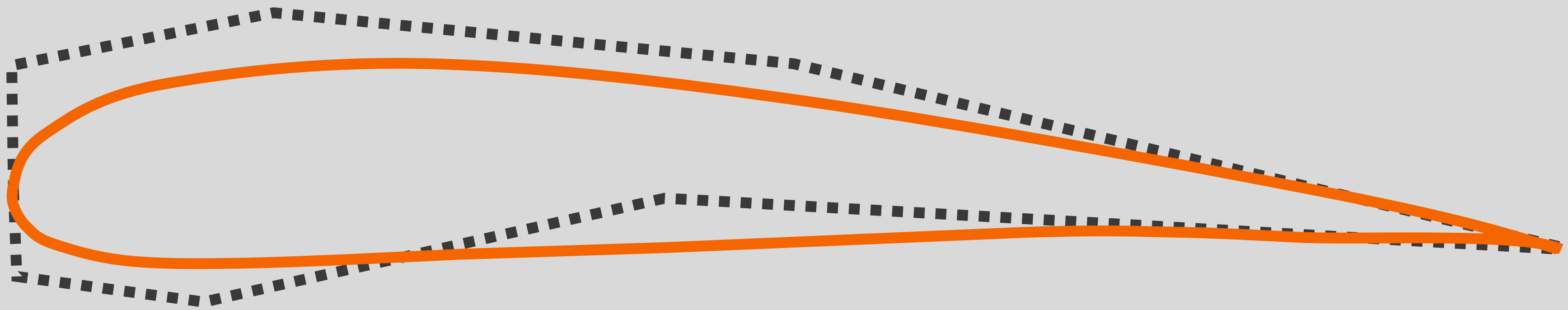
- The computational algorithm attempts to minimize the overall error between the proposed curve polynomial and the given set of points

- It is often considered more suitable than interpolation techniques as it can generate a **smoother** – and thus more manufacturable - curve



II.C | Modeling: Free-Form

- Polynomial uses the points as control points to influence the shape/propagation
- Part of the most famous freeform modeling methods is Bezier Curves and Surfaces, named after French mathematician Pierre Bezier
- Curves possess multiple properties such as invariance to rotation and translation, as well as the ability to perform local modifications
- Most suitable modeling for design and manufacturing



Knowledge Check

Interpolation, Approximation and Freeform are…

A. Modeling techniques for geometrical representation
B. Design Parameters to model surfaces
C. Topological concepts for creation of bodies

Knowledge Check

Interpolation, Approximation and Freeform are...

A. Modeling techniques for geometrical representation
B. Design Parameters to model surfaces
C. Topological concepts for creation of bodies

Knowledge Check

Most Suitable Geometrical Representation for Manufacturing is...

A. Implicit
B. Explicit
C. Parametric

Knowledge Check

Most Suitable Geometrical Representation for Manufacturing is...

A. Implicit
B. Explicit
C. **Parametric**

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Manufacturing References

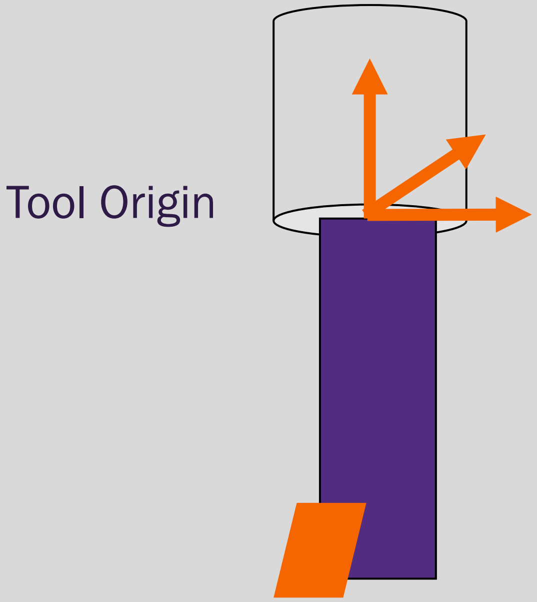
Section III

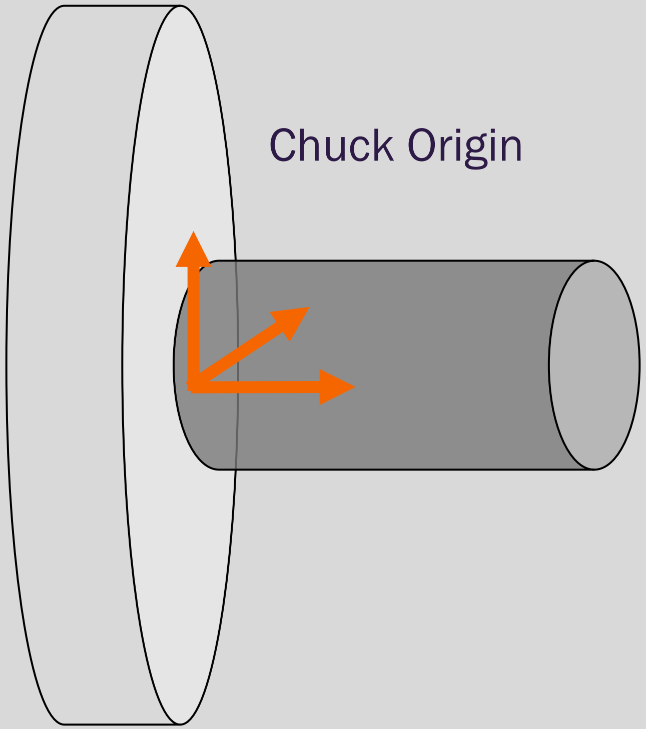
III.A | Geometrical Transformation

- There exist multiple references in manufacturing machines that needs to be coordinated
- Some of these references are fixed and do not change when we load a new part
- Typically, a tool holder reference/position and a table reference position constitutes those fixed references
- Every time we load a new tool to the machine, we need to add tool correction reference
- The most important step, is the programming reference and to set the work coordinate system on the machine

III.B | Machine References

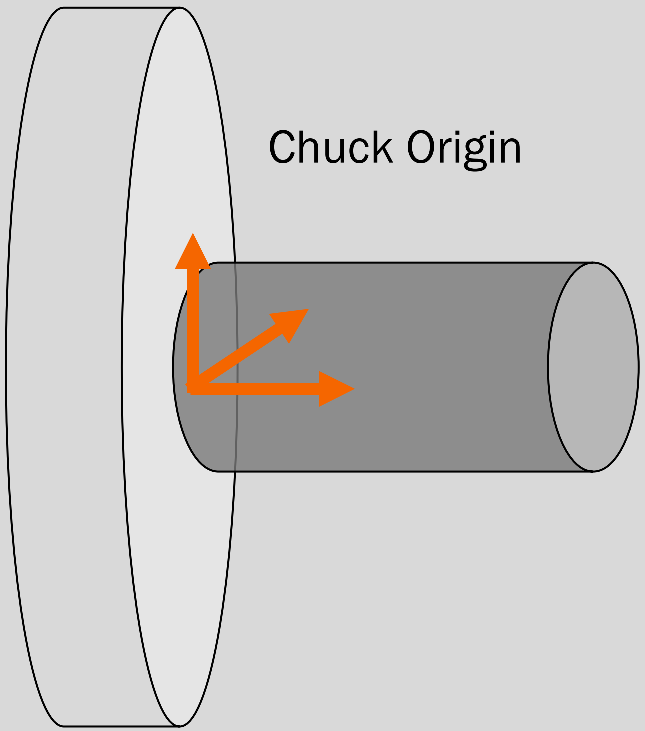
- These references are **fixed** in the machine and do not change
- Typically, we have one reference for the **tool holder**
- And another for the **table** (milling) / **chuck** (turning)

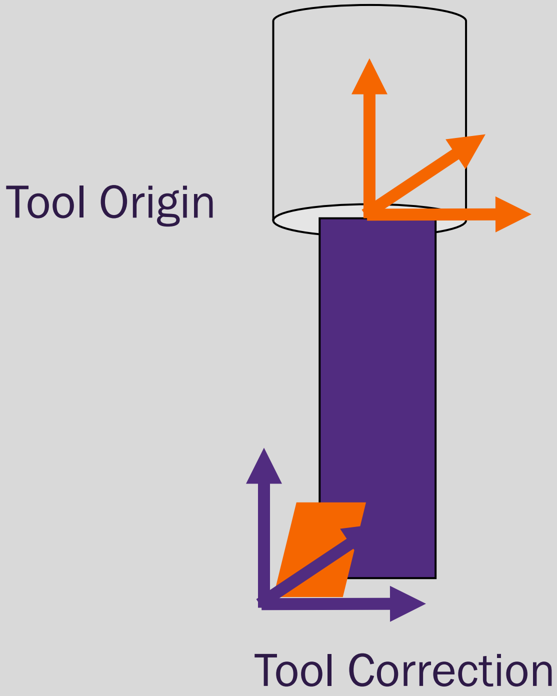




III.C | Tool Reference and Correction

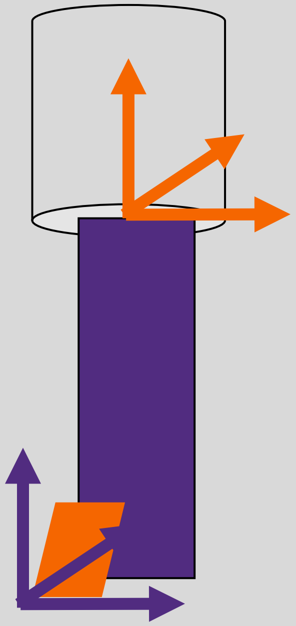
- We create the tool correction with the addition of new tools
- This ensures that we cut with the tool tip and not the tool holder
- Multiple beginner mistakes are generated from this reference

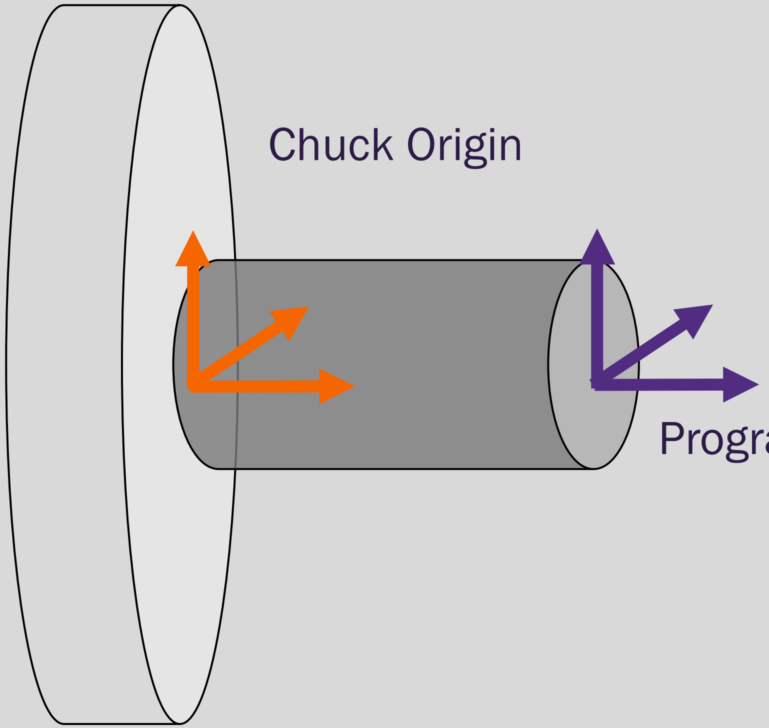




III.D | Programming Reference

- Needed every time we load a new part
- Ensures the programming reference in your CAM system is the same as on the machine
- Typically follows the Z convention





Knowledge Check

Which Reference do we Define Every Time we Load a New Part?

A. Tool Correction
B. Machine reference
C. Workpiece Coordinate
D. Tool Position

Knowledge Check

Which Reference do we Define Every Time we Load a New Part?

A. Tool Correction
B. Machine reference
C. Workpiece Coordinate
D. Tool Position

Knowledge Check

Tool Correction Accounts For...

A. Material of the tool
B. Number of flutes/inserts
C. Geometry of the tool

Knowledge Check

Tool Correction Accounts For…

A. Material of the tool
B. Number of flutes/inserts
C. Geometry of the tool

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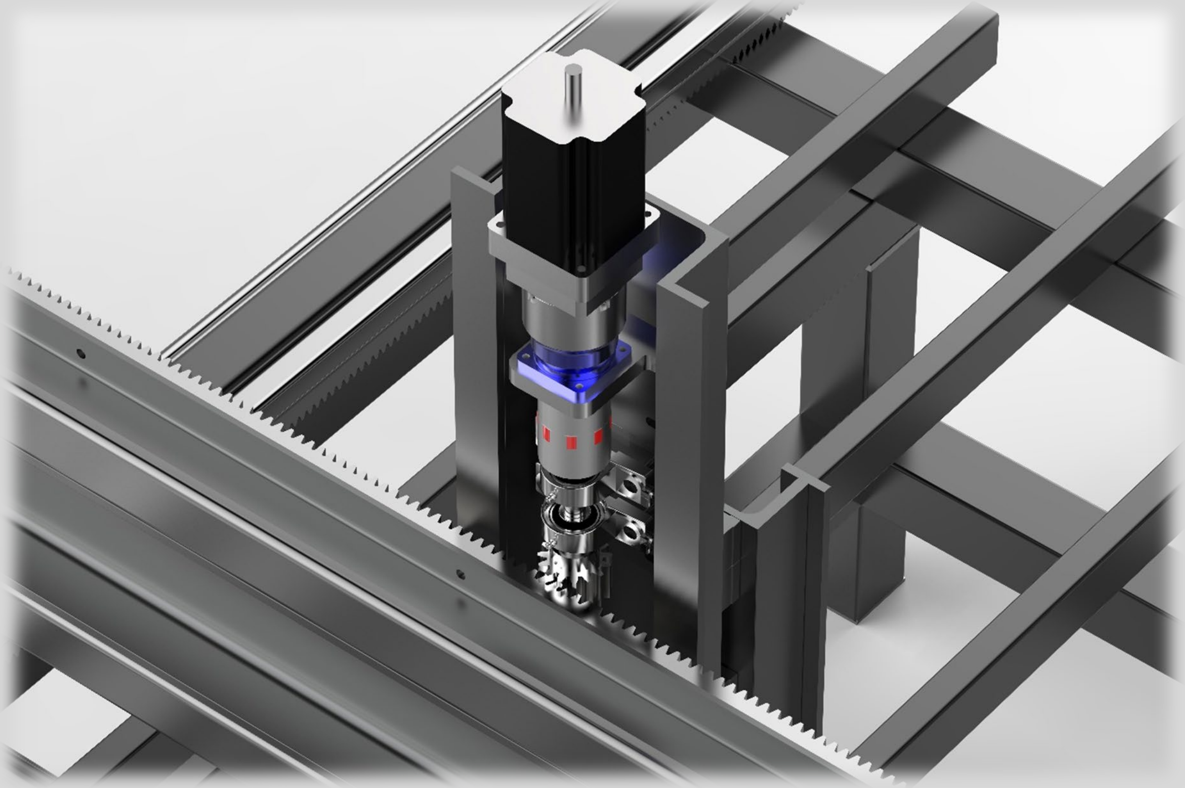
G-Code

Section IV

IV.A | What is a G-Code?

- List of coded instructions that the machine translated using numerical control units to machine movement
- It instructs the machine both of functions (calling a tool, starting lubrication…) and movement (go to certain position…)
- It was initially developed at the MIT Servomechanisms laboratory in the 1950s



IV.B | Definitions

- N: Block Number
- G: Preparatory Function
- X: Movement along the X orientation
- Y: Movement along the Y orientation
- Z: Movement along the Z orientation
- F: Feed rate
- M: Misc functions
- S: Spindle Speed
- T: Tool Management

IV.C | Main Program Structure

- Initialization
  - Deciding on units
  - Setting the machine parameters
  - Defining the workpiece coordinate system
  - Calling the appropriate tool
- Motion
  - Generating the Manufacturing Operation
  - Deciding on cutting conditions
- Ending
  - Retreat of Tool holder
  - Shutting down motions and speeds

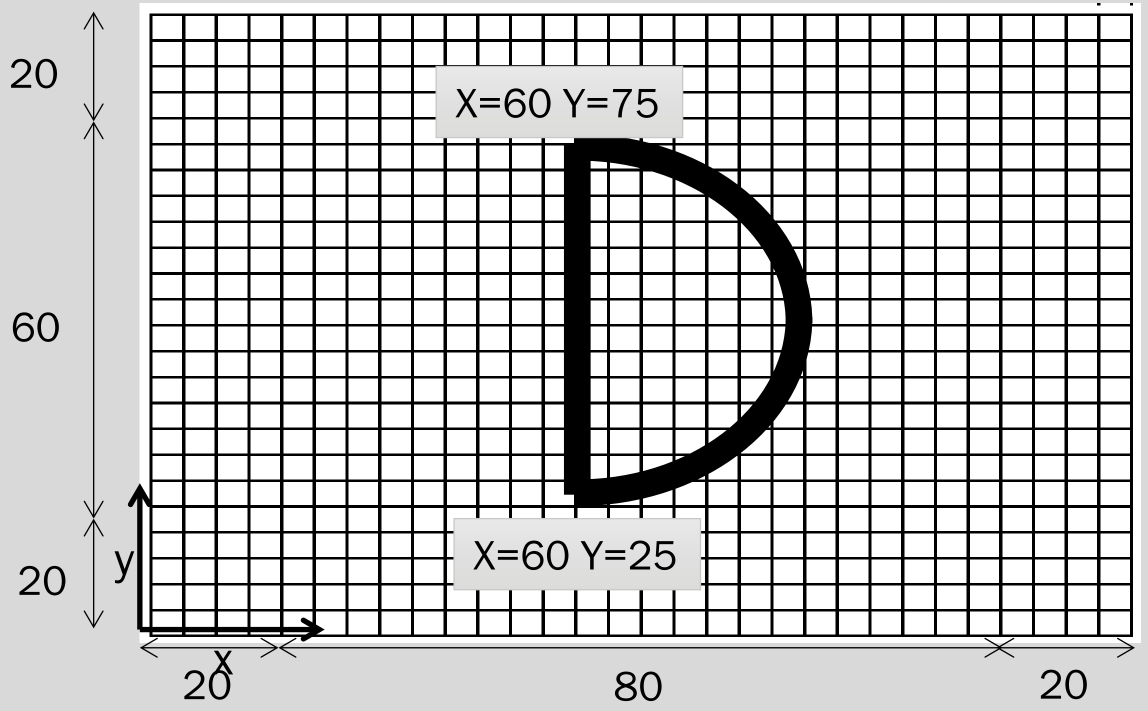
IV.D | G-Codes

- G-codes are used to determine the geometry of tool movements and the operation of the machine controller.
- Most famous ones are G0, G1, G2 and G3

G code	Function
G0	Positioning (Rapid Traverse)
G1	Linear Interpolation (Feed)
G2	Circular Interpolation CW
G3	Circular Interpolation CCW

Knowledge Check

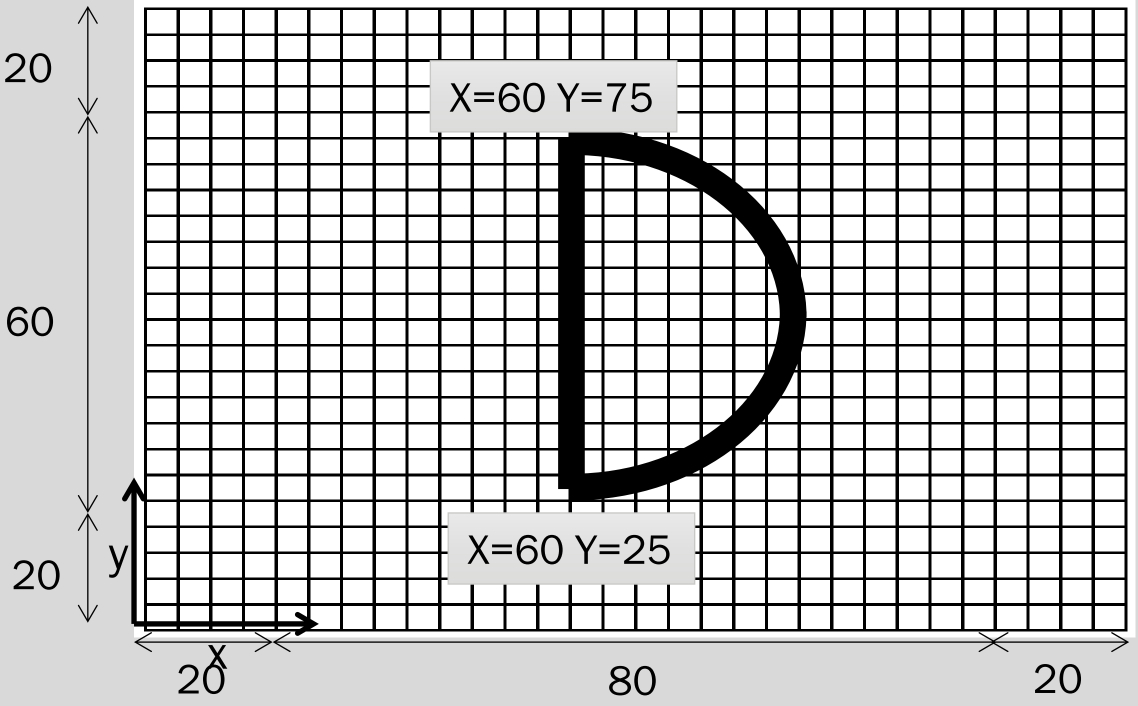
Write a G-code that engraves the letter D at 5mm depth on a 120mm x 100mm x 10mm rectangular billet. Take a 20mm of clearance. Use a fictive manufacturing tool of null diameter.



Knowledge Check

Write a G-code that engraves the letter D at 5mm depth on a 120mm x 100mm x 10mm rectangular billet. Take a 20mm of clearance. Use a fictive manufacturing tool of null diameter.

```
G0 X60 Y25 Z10
G1 Z-5
G1 Y75
G2 X60 Y25 R25
G1 Z10
```



IV.E | Sample G-Code

- %
- 001114
- G00 G20 G40 G80 G90 G58
- G00 G90 G53 Z0

- (OPERATION SURFACING)
- M06 T4
- G43 H04 D04
- G00 G90 G58
- G00 X-0.5 Y-2. S1500 M03
- G00 Z3.

- M08
- G01 Z-0.05 F30.
- G01 Y2.
- G01 X0.5
- G01 Y-2.
- M05
- M09

- G00 G90 G53 Z0
- M01

- (OPERATION DRILLING)
- M06 T3
- G43 H03 D03
- G00 G90 G58
- G00 X0 Y1. S5000 M03
- G00 Z3.

- M08
- G98 G81 Z-1.25 R0.1 F20.
- Y2.
- G80

- (END CYCLE)
- M05
- M09
- G00 G90 G53 Z0
- G00 G90 G53 Y0
- M30
- %

IV.E | Sample G-Code

- %
- O01114
- G00 G20 G40 G80 G90 G58
- G00 G90 G53 Z0

- (OPERATION SURFACING)
- M06 T4
- G43 H04 D04
- G00 G90 G58
- G00 X-0.5 Y-2. S1500 M03
- G00 Z3.

- M08
- G01 Z-0.05 F30.
- G01 Y2.
- G01 X0.5
- G01 Y-2.
- M05
- M09

- G00 G90 G53 Z0
- M01

M06 T4 Change to tool 4
G43 Create offsets from the positive direction
H04 Length by the value calibrated in H04
D04 diameter by the value calibrated in D04

- (OPERATION DRILLING)
- M06 T3
- G43 H03 D03
- G00 G90 G58
- G00 X0 Y1. S5000 M03
- G00 Z3.
- 0.1 F20.
- Y2.
- G80

- (END CYCLE)
- M05
- M09
- G00 G90 G53 Z0
- G00 G90 G53 Y0
- M30
- %

IV.E | Sample G-Code

- %
- O01114
- G00 G20 G40 G80 G90 G58
- G00 G90 G53 Z0

- (OPERATION SURFACING)
- M06 T4
- G43 H04 D04
- G00 G90 G58
- G00 X-0.5 Y-2. S1500 M03
- G00 Z3.

- M08
- G01 Z-0.05 F30.
- G01 Y2.
- G01 X0.5
- G01 Y-2.
- M05
- M09

- G00 G90 G53 Z0
- M01

G01 Z-0.05 Move linearly to z=-0.05
F30 At a feed rate of 30

- (OPERATION DRILLING)
- M06 T3
- G43 H03 D03
- G00 G90 G58
- G00 X0 Y1. S5000 M03
- G00 Z3.

- M08
- G98 G81 Z-1.25 R0.1 F20.
- Y2.
- G80

- (END CYCLE)
- M05
- M09
- G00 G90 G53 Z0
- G00 G90 G53 Y0
- M30
- %

IV.E | Sample G-Code

- %
- O01114
- G00 G20 G40 G80 G90 G58
- G00 G90 G53 Z0

- (OPERATION SURFACING)
- M06 T4
- G43 H04 D04
- G00 G90 G58
- G00 X-0.5 Y-2. S1500 M03
- G00 Z3.

- M08
- G01 Z-0.05 F30.
- G01 Y2.
- G01 X0.5
- G01 Y-2.
- M05
- M09

- G00 G90 G53 Z0
- M01

- (OPERATION DRILLING)
- M06 T3
- G43 H03 D03
- G00 G90 G58
- G00 X0 Y1. S5000 M03
- G00 Z3.

- M08
- G98 G81 Z-1.25 R0.1 F20.
- Y2.
- G80

- (END CYCLE)
- M05
- M09
- G00 G90 G53 Z0
- G00 G90 G53 Y0
- M30
- %

G98 Retract tool to starting z height,
G81 Start basic drilling cycle where tool drills in at feed rate and removes itself rapidly out
Z-1.25 drill into z= -1.25
R0.1 With drill retract .1
F20 At a feed rate of 20

Knowledge Check

M06 T01 is…

A. Calling Tool 01
B. Manufacturing 6 inches along the X Axis
C. Putting lubrication on

Knowledge Check

M06 T01 is…

A. Calling Tool 01
B. Manufacturing 6 inches along the X Axis
C. Putting lubrication on

Knowledge Check

Which G-Code command generates a work clock-wise circular tool movement?

A. G0 Y25 X32 Z4
B. G1 X2
C. G2 Y2 X3 Z2 R20
D. G3 X5 Y2 Z-4 R20
E. G4 Y4 Z3

Knowledge Check

Which G-Code command generates a work clock-wise circular tool movement?

A. G0 Y25 X32 Z4
B. G1 X2
C. G2 Y2 X3 Z2 R20
D. G3 X5 Y2 Z-4 R20
E. G4 Y4 Z3

Knowledge Check

Which G-Code command generates a rapid linear tool movement?

A. G0 Y25 X32 Z4
B. G1 X2
C. G2 Y2 X3 Z2
D. G3 X5 Y2 Z-4
E. G4 Y4 Z3

Knowledge Check

Which G-Code command generates a rapid linear tool movement?

A. G0 Y25 X32 Z4
B. G1 X2
C. G2 Y2 X3 Z2
D. G3 X5 Y2 Z-4
E. G4 Y4 Z3

Knowledge Check

Which G-Code line sets the feed rate value?

A. F100
B. S200
C. M6 T5
D. G1 X20

Knowledge Check

Which G-Code line sets the feed rate value?

A. F100
B. S200
C. M6 T5
D. G1 X20

THANK YOU

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- For more information:

  Email: harik@clemson.edu