# TA 202A

## Lecture 11

### Computer Numerical Control (CNC)

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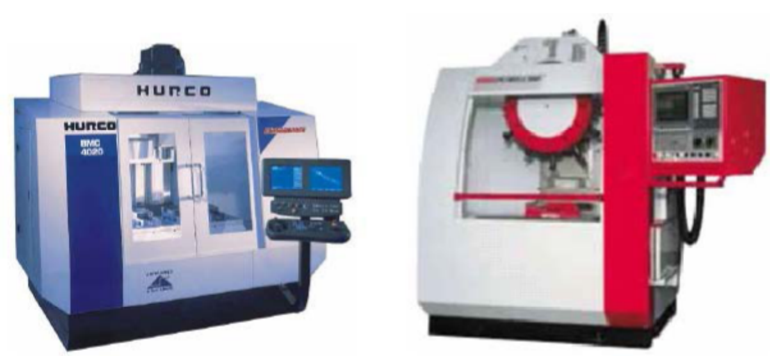
## Computer Numerical Control (CNC)



## Evolution of Machining Technology

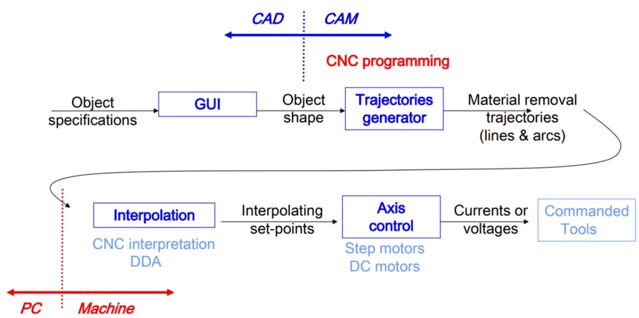
- Modification of existing machine tools with ***motion sensors*** and ***automatic advance*** systems.
- ***Closed-loop*** control systems for ***axis control.***
- Incorporation of the ***computational advances*** in the CNC machines.
- Development of ***high accuracy interpolation*** algorithms to trajectory interpolation.
- Resort to ***CAD systems to design parts*** and to manage the use of CNC machines.



## Evolution of Numerical Control

- Numerical Control (NC)
  - Data on paper or received in serial port
  - NC machine unable to perform computations
  - Hardware interpolation
- Computer Numerical control (CNC)
  - A computer is on the core of each machine tool
  - Computation and interpolation algorithms run on the machine
- Direct Numerical Control (DNC)
  - Central computer control a number of machines DNC or CNC
- Distributive numerical control
  - Scheduling
  - Quality control
  - Remote monitoring

# Methodology CAD/CAM




Use technical data from a database in the design and production stages. Information on parts, materials, tools, and machines are integrated.

CAD (Computer Aided Design): Allows the design in a computer environment.

**Ideas ⟶ Design**

CAM (Computer Aided Manufacturing) : To manage programs and production stages on a computer.

**Design ⟶ Product**



# Computer Numerical Control (CNC)

**Objectives**

- Increase accuracy, reliability, and ability to introduce changes/new designs
- Increase workload
- Reduce production costs
- Reduce waste due to errors and other human factors
- Carry out complex tasks (e.g. Simultaneous 3D interpolation)
- Increase precision of the produced parts.

**Advantages**

- Reduce the production/delivery time
- Reduce costs associated to parts and other auxiliary
- Reduce storage space
- Reduce time to start production
- Reduce machining time
- Reduce time to market (on the design/redesign and production).

**Limitations**

- High initial investment (30k€ to 1500k€)
- Specialized maintenance required
- Does not eliminates the human errors completely
- Requires more specialized operators
- Not so relevant the advantages on the production of small or very small series.

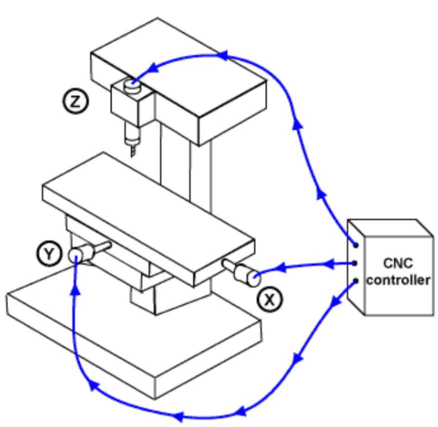
# Types of CNC machines

- *Based on Motion Type:*
  Point-to-Point or Continuous path
- *Based on Control Loops:*
  Open loop or Closed loop
- *Based on Power Supply:*
  Electric or Hydraulic or Pneumatic
- *Based on Positioning System*
  Incremental or Absolute

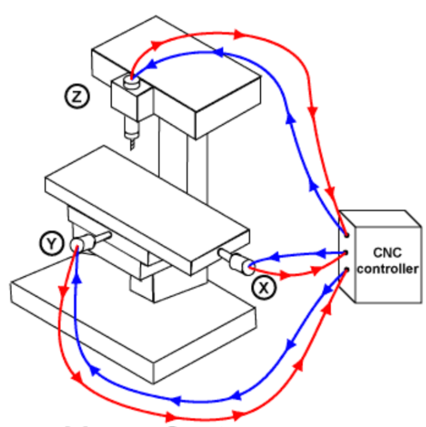


# Numeric Control

**Architecture of a NC system: 3 axis**



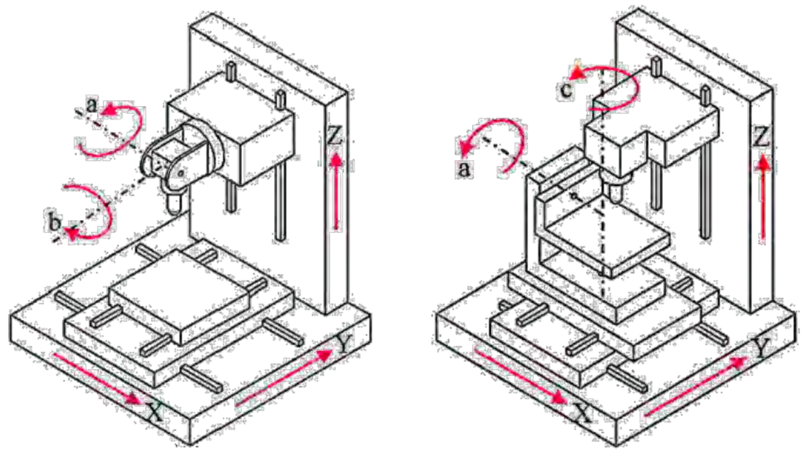

**Open loop system**




**Closed loop system**

# Numeric Control

**Architecture of a NC system: 5 axis**




Standard configurations of the rotary axes on 5–axis CNC machines, an orientable-spindle machine (left) and orientable-table machine (right)

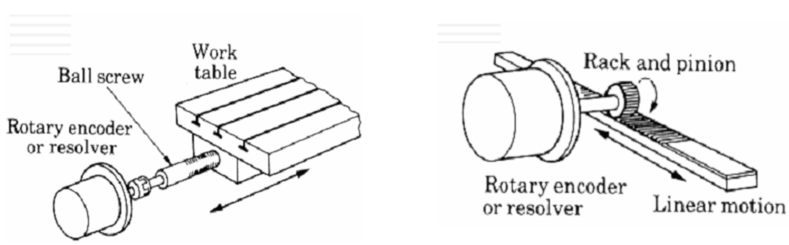


# Components of Servo-motor controlled CNC

Motor → lead screw rotation → table moves

↓

Motor speed control ← feedback ← position sensed by encoder




Two types of encoder configurations

## Motion Control and feedback

Encoder outputs: electrical pulses (e.g., 500 pulses per revolution)

Rotation of the motor → linear motion of the table: by the **leadscrew**

The **pitch** of the leadscrew: horizontal distance between successive threads

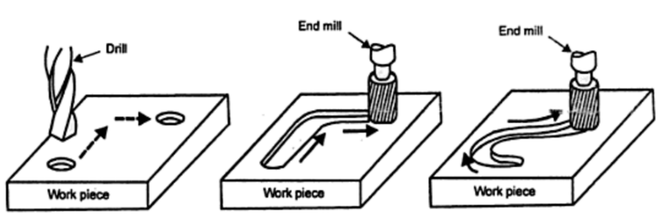
One thread in a screw ➔ **single start screw**: Distance moved in 1 rev = pitch

Two threads in screw ➔ **double start screw**: Distance moved in 1 rev = 2* pitch



## Type of CNC based on Motion Type

- **Point to Point -** Moving at maximum rate from point to point. Accuracy of the destination is important but not the path. It has No contouring capability
- **Straight cut control-** one axis motion at a time is controlled for machining
- **Contouring-** Multiple axis's controlled simultaneously




(a) Point - to point control (drilling machines, welding) (b) Straight - cut control (Milling machines, lathes) (c) Contouring control (Machine centers)

# CNC terminology

**BLU** (Basic Length Unit): smallest programmable move of each axis.
For example, 1 BLU = 0.0001" means that the axis will move 0.0001" for every one electrical pulse received by the motor. The BLU is also referred to as Bit (binary digit).

**Pulse = BLU = Bit**

**Controller** (Machine Control Unit, MCU): Electronic and computerized interface between operator and m/c

Controller components:

***Data Processing Unit (DPU):***

- Input device [RS-232 port/ Tape Reader/ Punched Tape Reader]
- Data Reading Circuits and Parity Checking Circuits
- Decoders to distribute data to the axes controllers.

***Control Loops Unit (CLU) :***

- Interpolator to supply machine-motion commands between data points
- Position control loop hardware for each axis of motion



## Example 1

**A Stepping motor of 200 steps per revolution is mounted on the leadscrew (assume single start screw) of a drilling machine. If the pitch is 0.1 in/ rev.,**

**(a) What is the BLU of the system ?**

$$BLU = \frac{0.1}{200} = 0.0005"$$

**(b) If the motor receives a pulse frequency of 2000 pulses per second (pps), what is the linear velocity in inch/min ?**

$$V = p(RPM) = 0.1 \times \left(\frac{2000 \times 60}{200}\right) = 60\ in/min$$

### Example 2

**A DC servo-motor is coupled to a leadscrew (pitch = 5mm, single start) of a machine table. A digital encoder, which emits 500 pulses per revolution, is mounted on the leadscrew. If the motor rotates at 600 rpm (1:1 gear ratio), find**

**(a) The linear velocity of the table**

$$V = p(RPM) = 5 \times 600 = 3000\ mm/\min = 3m/min$$

**(b) The BLU of the machine**

$$BLU = \frac{5}{500} = 0.01\ mm$$

**(c) The frequency of pulses transmitted by the encoder.**

$$RPM = 600 = \frac{60f}{500}$$

$$f = 5000\ Hz$$

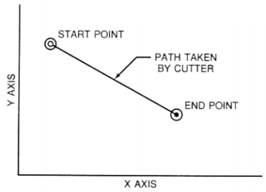


## Interpolation

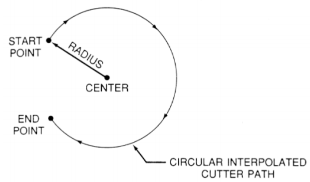
- To calculate the intermediate points of a curve, given its starting and end coordinates.
- Required for machining straight surfaces that are not parallel to either of the coordinate axes.

**Types of Interpolation:**

- Linear interpolation
  Straight line between two points in space
- Circular interpolation
  Circular arc defined by starting point, end point, center or radius, and direction
- Helical interpolation
  Circular plus linear motion
- Parabolic and cubic interpolation
  Free form curves using higher order equations




*linear interpolation*



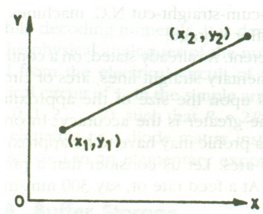

*circular interpolation*

# Interpolation

Linear Interpolation:

Coordinates of successive intermediate points:

(calculated from the consideration that distances $(x_2-x_1)$ and $(y_2-y_1)$ must be traversed in equal time)

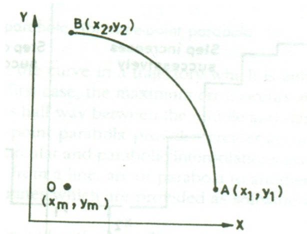



$$x_s = x_1 + \sum_{s=1}^{n}\left[\frac{x_2 - x_1}{n}\right]_s$$

$$y_s = y_1 + \sum_{s=1}^{n}\left[\frac{y_2 - y_1}{n}\right]_s$$

$n$ = total number of steps between points $A$ and $B$,
$s$ = sequence number of the particular step

Circular Interpolation:




$$x_s = x(\mu) \approx x_1 - \sum_{s=1}^{s=\mu} \frac{y(s-1) - y_m}{n}$$

$$y_s = y(\mu) \approx y_1 + \sum_{s=1}^{s=\mu} \frac{x(s-1) - x_m}{n}$$

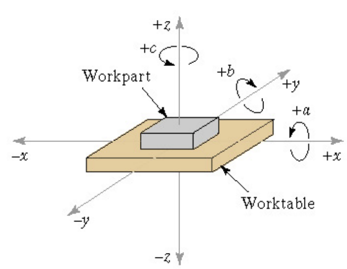
$n$ = total number of steps between $A$ and $B$
$s$ = sequence number of the particular step
$\mu$ = instantaneous value of the stepwise change in $s$.



# NC Coordinate Systems

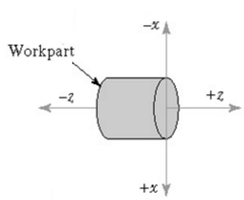
For flat and prismatic (block-like) parts:

- Milling and drilling operations
- Conventional Cartesian coordinate system
- The X axis controls the table movement left or right
- The Y axis controls the table movement toward or away from the column.
- The Z axis controls the vertical movement of the spindle.
- +Z moves away from the workpiece or the spindle
- Rotational axes about each linear axis




For rotational parts:

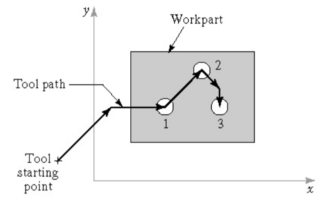
- Turning operations
- Only *x*- and *z*-axes



# Motion Control Systems

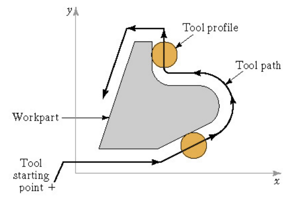
**Point-to-Point systems**

- Also called position systems
- System moves to a location and performs an operation at that location (e.g., drilling)
- Also applicable in robotics




**Continuous path systems**

- Also called contouring systems in machining
- System performs an operation during movement (e.g., milling and turning)





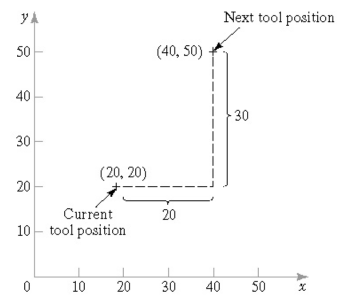

# Absolute vs. Incremental Positioning

**Absolute positioning**

*Move is: x* = 40, *y* = 50

**Incremental positioning**

*Move is: x* = 20, *y* = 30.

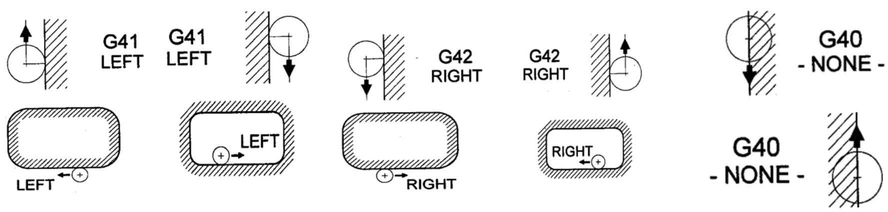


# Cutter Compensation

Cutter compensation is used to offset the center of the cutter, and shift it the distance of the radius, to the specified side of the programmed path.

- G41 will select cutter compensation left; that is the tool is moved to the left of the programmed path to compensate for the radius of the tool.
- G42 will select cutter compensation right; that is the tool is moved to the right of the programmed path to compensate for the radius of the tool.
- G40 will cancel the G41 or G42 cutter compensation commands.

**N_G41 D_**




Cutter Compensation Left    Cutter Compensation Right    Cutter Compensation Cancel



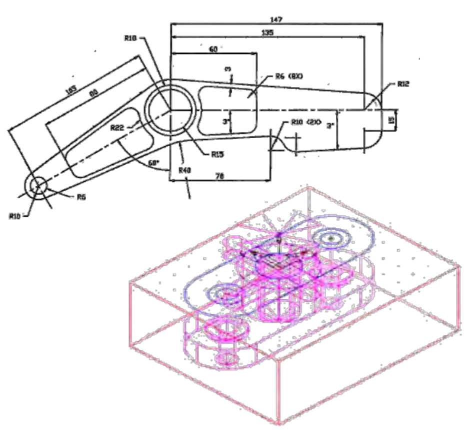
# CNC Programming

- CNC machines know how to do interpolation, but not how to machine a complete part.
- CAM helps to bridge the gap between object shapes and making material removal trajectories (to be interpolated).
- In other words, one needs to do CNC programming.

In the following: G-code (also RS-274), which has many variants, is the common name for the most widely used numerical control (NC) programming language.

Steps 1, 2, ... 6, to execute a part

**1.** Read and interpret the technical drawings



# CNC Programming

**2.** Choose the most adequate **machine** for the several stages of machining
Relevant features:

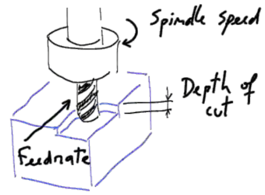
- The workspace of a machine versus the part to be produced
- The options available on each machine
- The tools that can be used
- The mounting and the part handling
- The operations that each machine can perform

**3.** Choose of the most adequate **tools** Relevant features:

- The material to be machined and its characteristics
- Standard tools cost less
- The quality of the mounting part is function of the number of parts to produce
- Use the right tool for the job
- Verify if there are backup tools and/or stored available
- Take into account tool aging

**4.** Cutting data

- Spindle Speed – speed of rotation of the cutting tool (rpm)
- Feed rate – linear velocity of advance to machine the part (mm/minute)
- Depth of Cut – depth of machining in z (mm)






# CNC Programming

**5.** Choice of the interpolation plane, in 2D machines


**5.1.** Unit system imperial / inches (G70) or international millimeters (G71).
**5.2.** Command mode*
Absolute = use world coordinate system (G90)
Relative = move w.r.t. the current position (G91)
* There are other command modes, e.g. helicoidal.

# CNC Programming

**6. Data Input**

| | |
|---|---|
| **O** | Program Number |
| **N** | Sequence **N**umber |
| **G** | Preparatory Functions |
| **X** | **X** Axis Command |
| **Y** | **Y** Axis Command |
| **Z** | **Z** Axis Command |
| **R** | **R**adius from specified center |
| **A** | **A**ngle ccw from +X vector |
| **I** | X axis arc center offset |
| **J** | Y axis arc center offset |
| **K** | Z axis arc center offset |
| **F** | **F**eed rate |
| **S** | **S**pindle speed |
| **T** | **T**ool number |
| **M** | **M**iscellaneous function |



# Manual Part Programming

**Part program**: A computer program to specify
- Which tool should be loaded on the machine spindle;
- What are the cutting conditions (speed, feed, coolant ON/OFF etc.)
- The start point and end point of a motion segment
- how to move the tool with respect to the machine.

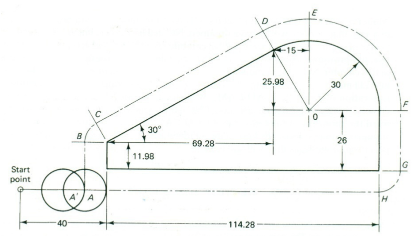
**Standard Part programming language**: RS 274-D (Gerber, GN-code)
The RS274-D is a **word address format**
Each line of program = 1 **block**
Each block is composed of several instructions, or (words)

Sequence and format of words:
N3 G2 X+1.4 Y+1.4 Z+1.4 I1.4 J1.4 K1.4 F3.2 S4 T4 M2

sequence no
preparatory function
destination coordinates
dist to center of circle
feed rate
spindle speed
tool
Other function

# Manual Part Programming

**Example-1**




| | |
|---|---|
| N005 G71 G90 G97 G94 T01 | Global Parameters, Metric, Absolute, V[rev/min], f[mm/min] |
| N010 G00 X -10 Y -10 | Movement of Tool from 0 to A |
| N015 G01 Z -5 F 2 | Movement of tool from above the part to A |
| N020 M03 S2000 | Spindle ON, CW, Speed 2000 rpm |
| N025 X 114.28 F 0.3 | (G01, Y -10, Z -5 may not be repeated) From A to H |
| N030 G03 X (114.28+10) Y0 R10 | From H to G, circular interpolation, CCW, Y value changes from -10 to 0 |
| N035 G01 Y26 From G to F | |
| N040 G03 X(69.28-10Sin300) Y(26+25.98+10Cos300) R40 | From F to D |
| N045 G01 X(0-10Sin300) Y(11.98+10Cos300) | From D to C |
| N050 G03 X -10 Y 11.98 R 10 | From C to B |
| N055 G01 X -10 Y -10 | From B to A |
| N060 Z 5 | |
| N065 M02 | End of Program |



# Other Important Functions

Important G codes

| | |
|---|---|
| G00 | Rapid Transverse |
| G01 | Linear Interpolation |
| G02 | Circular Interpolation, CW |
| G03 | Circular Interpolation, CCW |
| G17 | XY Plane |
| G18 | XZ Plane |
| G19 | YZ Plane |
| G20/G70 | Inch units |
| G21/G71 | Metric Units |
| G40 | Cutter compensation cancel |
| G41 | Cutter compensation left |
| G42 | Cutter compensation right |
| G43 | Tool length compensation (plus) |
| G43 | Tool length compensation (plus) |
| G44 | Tool length compensation (minus) |
| G49 | Tool length compensation cancel |
| G80 | Cancel canned cycles |
| G81 | Drilling cycle |
| G82 | Counter boring cycle |
| G83 | Deep hole drilling cycle |
| G90 | Absolute positioning |
| G91 | Incremental positioning |

Important M codes

| | |
|---|---|
| M00 | Program stop |
| M01 | Optional program stop |
| M02 | Program end |
| M03 | Spindle on clockwise |
| M04 | Spindle on counterclockwise |
| M05 | Spindle stop |
| M06 | Tool change |
| M08 | Coolant on |
| M09 | Coolant off |
| M10 | Clamps on |
| M11 | Clamps off |
| M30 | Program stop, reset to start |

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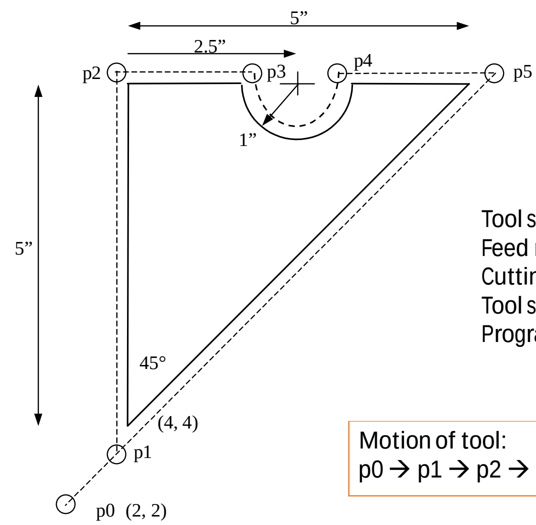
# Manual Part Programming

**Example-2**

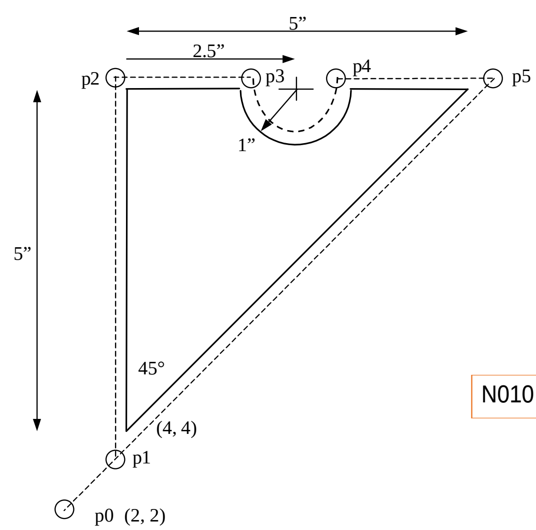



Tool size = 0.25 inch,
Feed rate = 6 inch per minute,
Cutting speed = 300 rpm,
Tool start position: 2.0, 2.0
Programming in inches

Motion of tool:
p0 → p1 → p2 → p3 → p4 → p5 → p1 → p0



## 1. Set up the programming parameters




Dimensions in inches

Use absolute coordinates

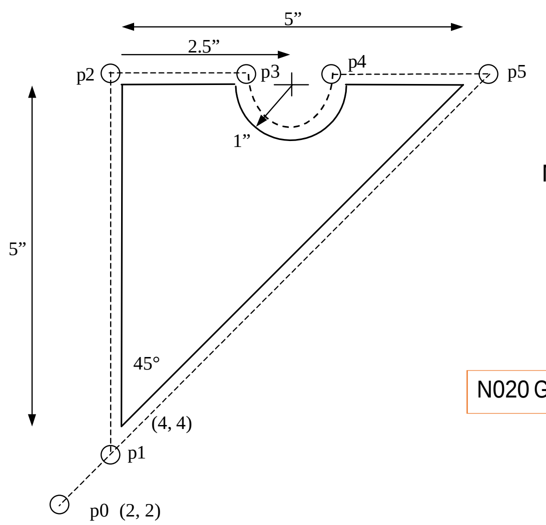
Feed in ipm

N010 G70 G90 G94 G97 M04

Spindle speed in rpm

Spindle CCW

## 2. Set up the machining conditions




Machine moves in XY-plane

Use full-circle interpolation

Feed rate

Spindle speed

N020 G17 G75 F6.0 S300 T1001 M08

Tool no.

Flood coolant ON

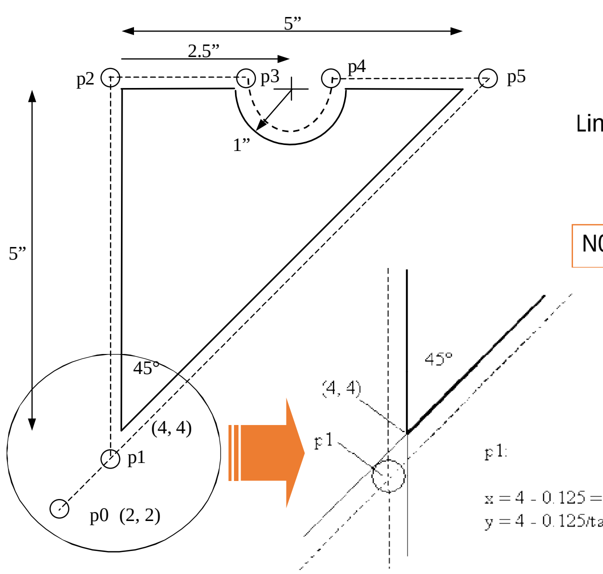


## 3. Move tool from p0 to p1 in straight line

Linear interpolation

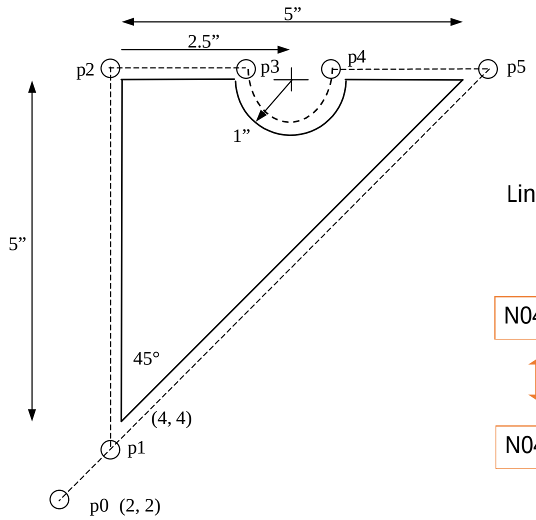
target coordinates

N030 G01 X3.875 Y3.698




$x = 4 - 0.125 = 3.875$
$y = 4 - 0.125/\tan 22.5 = 3.693$

## 4. Cut profile from p1 to p2




Linear interpolation

target coordinates

N040 G01 X3.875 Y9.125

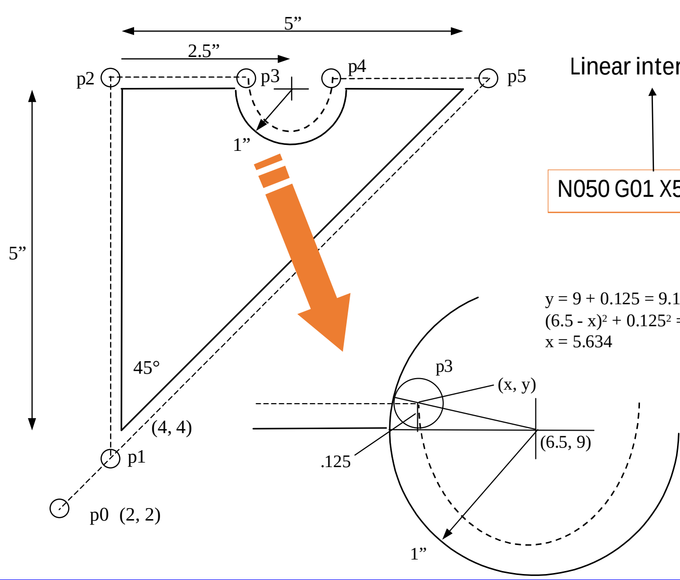
or

N040 G01 Y9.125

X-coordinate does not change ➔ no need to program it



## 5. Cut profile from p2 to p3




Linear interpolation

target coordinates

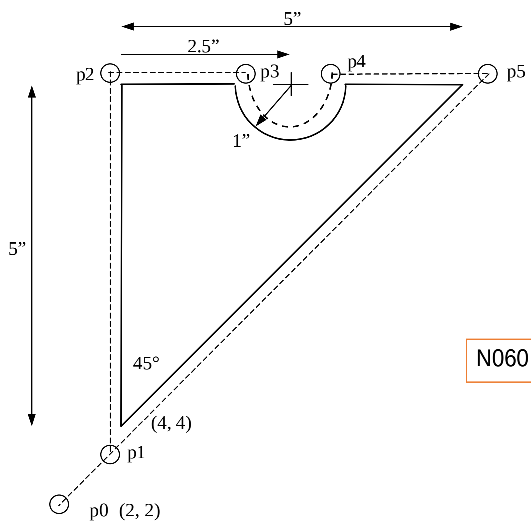
N050 G01 X5.634 Y9.125

$y = 9 + 0.125 = 9.125$

$(6.5 - x)^2 + 0.125^2 = (1 - 0.125)^2$

$x = 5.634$

## 6. Cut along circle from p3 to p4




circular interpolation, CCW motion

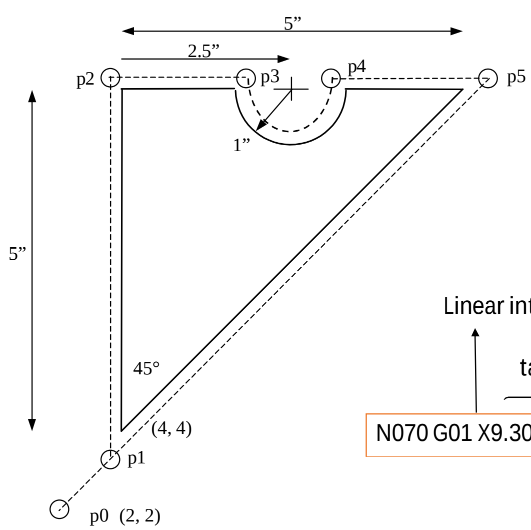
target coordinates

$$\boxed{\text{N060 G03 }\underbrace{\text{X7.366 Y9.125}}_{\text{target coordinates}}\ \underbrace{\text{I6.5 J9.0}}_{\text{coordinates of center of circle}}}$$

coordinates of center of circle



## 7. Cut from p4 to p5

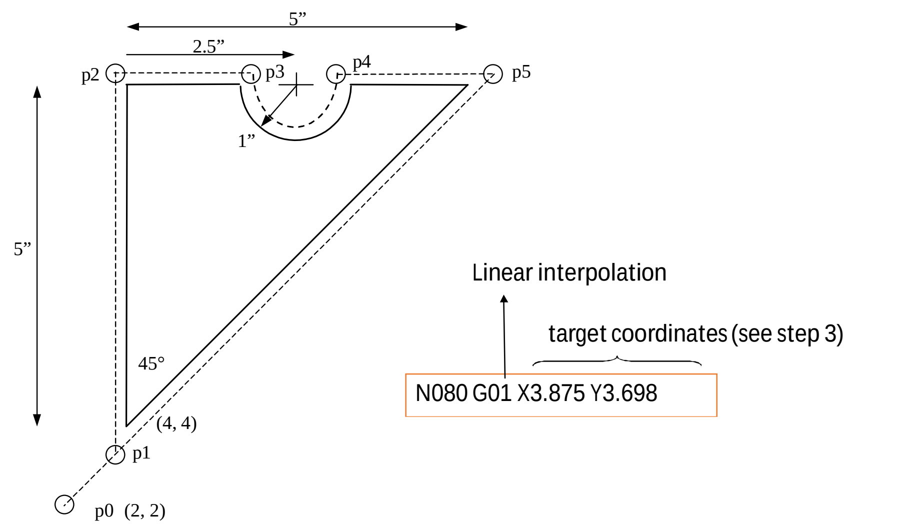



Linear interpolation

target coordinates (Y is unchanged)

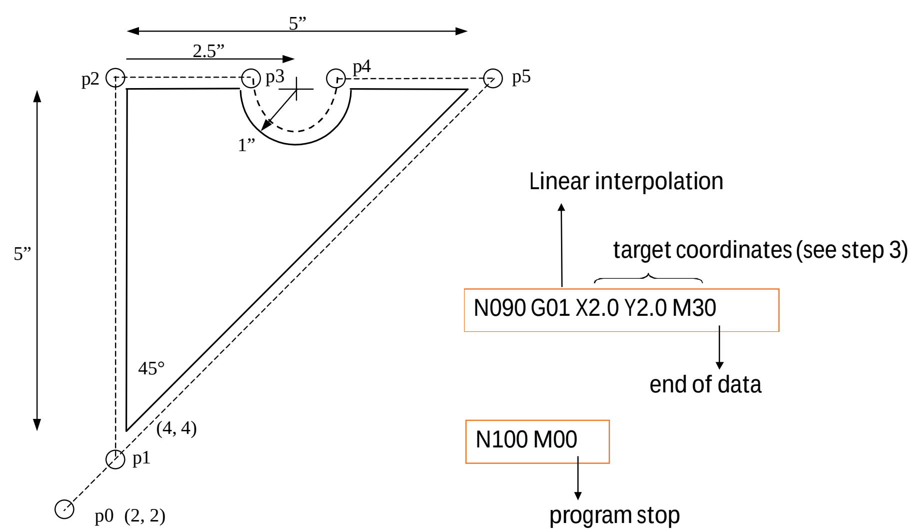
$$\boxed{\text{N070 G01 }\underbrace{\text{X9.302}}_{\text{target coordinates}}}$$

## 8. Cut from p5 to p1



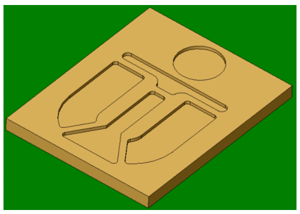



## 9. Return to home position, stop program



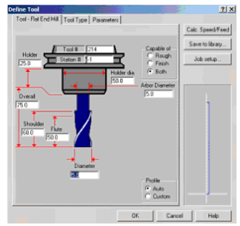
# Automatic Part Programming

Software programs (Example: CATIA etc.) can automatic generate CNC data

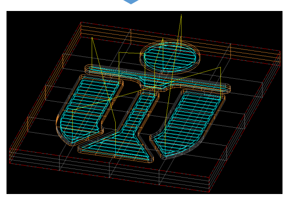


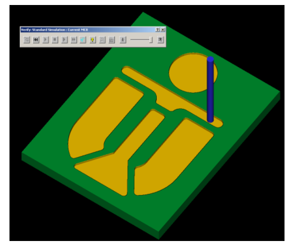
Make 3D model

Define Tool



CNC data





Simulate cutting

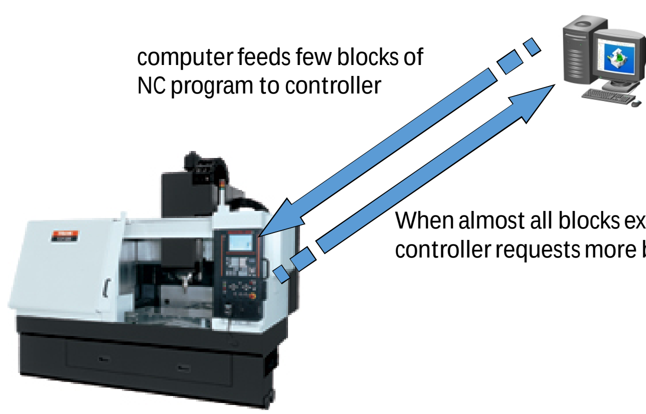


# Automatic part programming and DNC

Very complex part shapes ➔ very large NC program

NC controller memory may not handle HUGE part program

computer feeds few blocks of NC program to controller



When almost all blocks executed, controller requests more blocks

## Recap of this Topic

- Introduction to CNC machines
- Evolution of CNC machines
- Types of CNC machines
- CNC manual part programming
- Automatic part programming and DNC



## Next Lecture

Measurement and Metrology