COMPUTER NUMERICAL CONTROL OF MACHINE TOOLS

Laboratory for Manufacturing Systems and Automation
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Dr. Dimitris Mourtzis

Associate professor

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Chapter 1:
An Introduction to Numerical Control Machinery

Objectives of Chapter 1

- Evaluate which of your **manufacturing processes** are **good candidates for automation**
- Understand the **levels of automation** that can be achieved
- Discuss the **productivity gains** you can achieve through automation
- Devise an **automation plan**
- Describe the **types of automation** available in CAM Systems
- Understand how a database can be used to store **machining knowledge**

Objectives of Chapter 1

- Describe the difference between **direct and distributed Numerical Control (NC)**
- Describe **four ways** that **programs can be entered into a computer numerical controller**
- Explain **two tape code formats** in use with CNC machinery
- Give the **major objectives of Numerical Control**
- Describe the **difference between a numerical control tape machine and a Computer Numerical Control (CNC) machine**

Class Summary

Do you need to **boost your productivity** and **avoid** costly human **errors**?

Find out how you can
standardize your manufacturing processes and
develop an automation plan
to fit the needs of your business ***now*** and in the ***future***

(Ann Mazakas, ''The Art of Automation'', courses materials of ESPRIT World Conference on CNC)

Why Automate?

Why Automate?

Benefits of Automation

- Save **time**
- Reduce **human error**
- Make processes more **efficient**
- Eliminate **redundancies** and **wasted effort**
- Implement **process improvements** faster
- Use **skilled employees** for more valuable tasks
- **Avoid disruptions** when new employees are hired or longtime employees retire

Ann Mazakas, ''The Art of Automation'', courses materials of ESPRIT World Conference on CNC

Why Automate?

Reality Check

- **Don't automate just because:**
  - It seems like a **good idea**
  - You heard from a **salesman** that you'll save a ton of money
  - **Everyone** else/competitors/the guy next door is doing it
  - You want to **lay off** workers

- ***Automation takes time and resources***
- ***Do your homework before you decide***
- ***People don't want you to automate them out of a job***

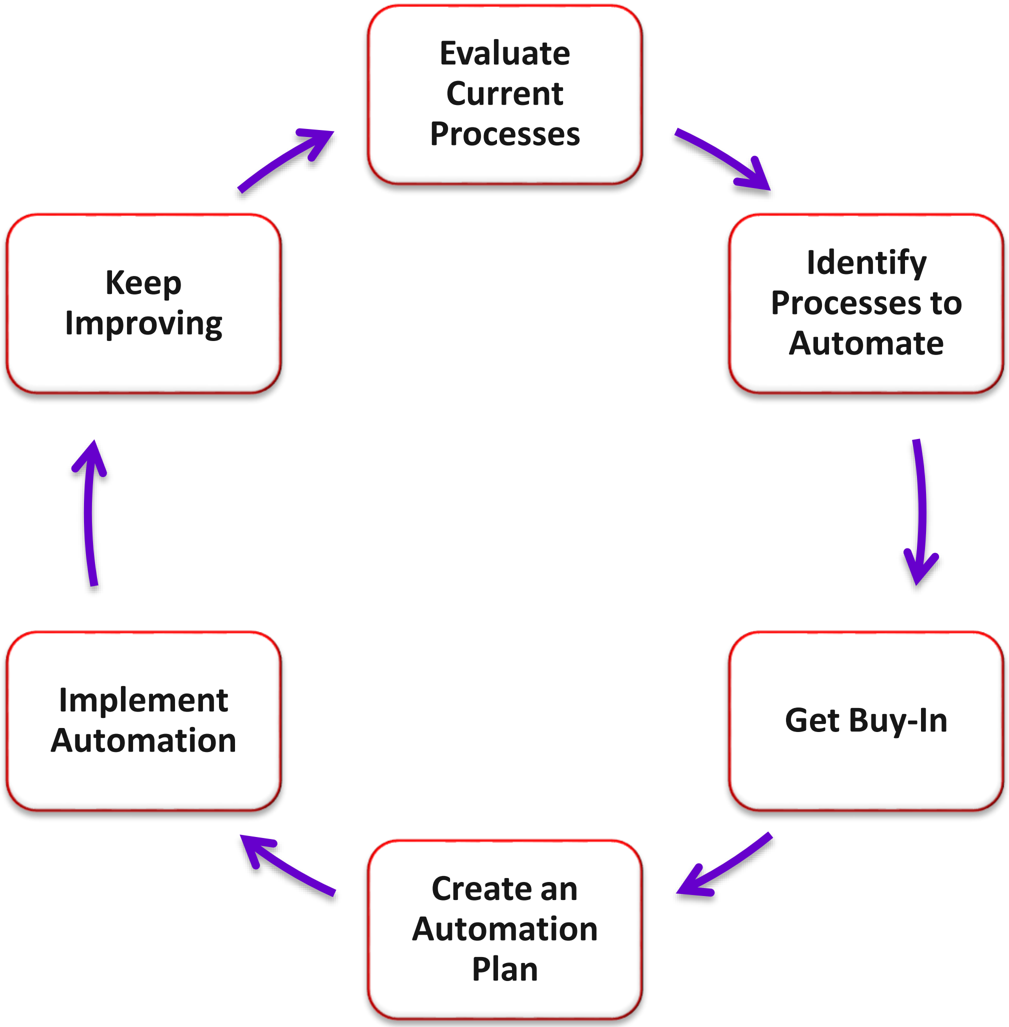
Why Automate?

Good Reasons to Automate

- **Improve quality** and **customer satisfaction**
- **Produce more** with the same equipment / people
- **Respond faster** to market changes
- **Expand business** into new markets

Why Automate?

Automation Lifecycle



Evaluate your current processes

Evaluate Your Current Processes

The Big Picture

- ***WALK THROUGH*** the entire process, from the time an order comes in until the order ships
- **Do not just look**, get out and literally **walk through each step**
- Observe and **ask questions**
- If you can, walk through other manufacturing facilities
- **Invite people** who don't know your processes to **walk through your facility**

Identify processes to automate

Identify Processes To Automate

Good Candidates for Automation

- **Tasks** that can be **repeated**
- **Tasks** that are **similar**
- **Tasks** that are **important**
- **Tasks** where **human error can be eliminated**
- **Tasks** with **known variables**

Identify Processes To Automate

Ask Yourself

- Are there **repetitive tasks** people are having problems with?
- Where do we ***lose the most time***?
- Where do we make the **most mistakes**?
- ***How far does each product travel*** before it makes it out the door?

Identify Processes To Automate

Seek and Destroy Broken Processes

- *Complacency is your enemy*! "Because we have always done it this way" is **NO EXCUSE**
- ***Do not automate anything that should not be done in the first place!***
- Use the lean mantra "**Eliminate waste**"

Identify Processes To Automate

Improve Processes Before Automating

- **Consistency is your friend**! It lets you know what to expect
- **Standardize the tools, materials, processes** you already have
- Study which **processes work well** and see if you can **apply those principles elsewhere**
- **Make processes flexible** so you can adapt to changes in the future

Identify Processes To Automate

What can you standardize?

- Cutting tools
- Fixtures and mounting
- Stock sizes (?)
- Machining operation defaults
- Machining processes
- Lot sizes (?)

Identify Processes To Automate

Classify by Urgency and Importance

- **Identify good candidates** by classifying tasks into **4 zones**

	Urgent	*Not Urgent*
	Zone 1: Important tasks that pop up suddenly and must be completed quickly - There is no time to automate.	**Zone 2:** Important tasks that are done on a regular basis - **Ideal candidates for automation**
Not Important	**Zone 3:** These tasks must get done quickly but are not important enough to be worth the time spent on automation	**Zone 4:** Never automate a task that is both unimportant and not urgent

Think Like the Boss

Think Like the Boss

Get Support from Upper Management

- **Management is looking for a return on investment (ROI)**
- **Here is how it works:**

- Standardization
- Consistency
- Automation
- Cheaper/Faster
- More Profit for the Company
- You Look Like a GENIUS

Think Like the Boss

Compare Benefits to Costs

- You need to demonstrate the **value of automation**
- How are you going to ***save the company time and money***
- Talk hard numbers to break through resistance to the **time and money spent on automation**

  - We can **increase throughput** by X pieces per day/month
  - We can **decrease scrap** and rework by X amount
  - We can **improve on-time deliveries** by X days
  - We can **eliminate back orders and get paid faster**
  - We can get a **new product** on the market X days **faster**

Think Like the Boss

Use Benchmarks to Get the Numbers

- **Get the actual costs of a current process**
  - Hourly labor rate/machine time/tools for a process that is a realistic reflection of work done on a regular basis
  - Rework/scrap caused by human error
  - Inspection time to catch human error
  - Wasted time on non-value-added work or, worse, waiting around
- **Calculate the estimated costs of an automated process**
  - Hourly labor rate/machine time/tools for the exact same process after it's automated
  - Rework, inspection, waste after automation
- **Multiply savings to show annual payback**
  - A few minutes every day can really add up
  - Compare the annual savings to the cost of software/equipment/training needed to implement automation

Think Like the Boss

Build Your Proof

- Show your ***lists of bottlenecks, quality issues, late shipments, lost opportunities*** etc.

- Show your **benchmark tests**

- **Offer different scenarios** to overcome budget resistance:
  - ***New equipment/software*** versus updating existing equipment/software
  - ***Automating a handful of processes*** versus all processes
  - ***Pilot program*** versus a company-wide rollout

Devise an automation plan

Devise an Automation Plan

Start Out Right

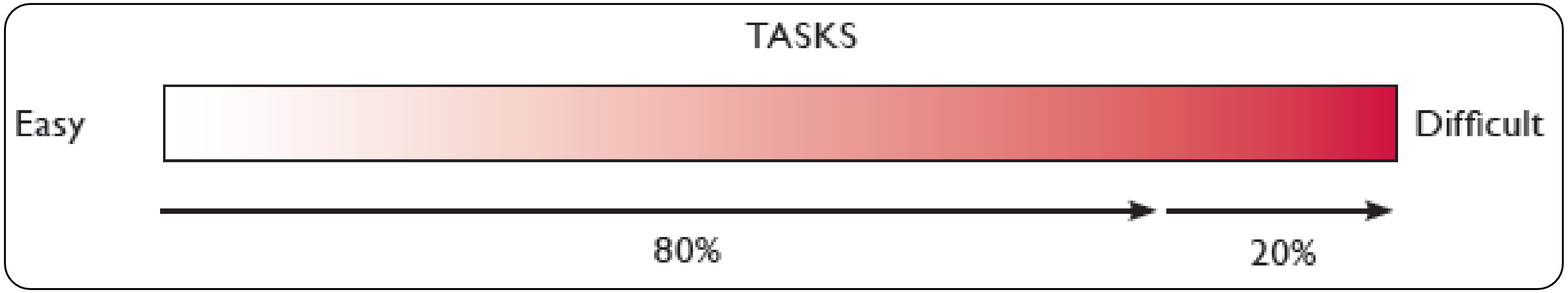
- **Choose the right project**
  - ➢ If possible, use a new project as a logical time to **implement newer better processes**
  - ➢ Choose a project with the **biggest payback**
  - ➢ Choose a project with the **least risk**

- **Get employees involved early**
  - ✓ Your employees and their knowledge are your most important assets
  - ✓ Get input from all levels
  - ✓ Communicate
  - ✓ Set goals
  - ✓ Show the benefits

Devise an Automation Plan

The 80/20 Rule – Pareto Principle

- **80% of tasks identified for automation will require about 20% of your time**
- The last 20% of tasks will take up to 80% of your time
- Use the 80/20 rule to decide whether that last 10-20% is worth the time involved to automate

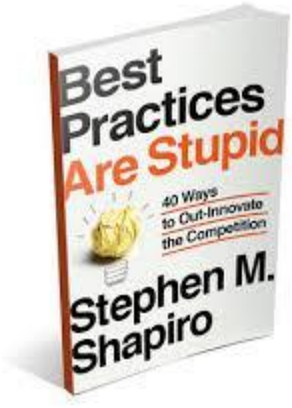


(Ann Mazakas, ''The Art of Automation'', courses materials of ESPRIT World Conference on CNC)

Devise an Automation Plan

Best Practices are Stupid *(sometimes)*

- If you use the same industry practices as everyone else, **what makes you different or better**?
- **Copying the competition** does not get you ahead
- **Stand out from the crowd**, create your own best practices
- ***Look outside your industry for ideas***
  - What can you learn from a racing pit crew?
  - What can you learn from a fast-food restaurant?
  - What can you learn from Netflix or Amazon?



Devise an Automation Plan

Look at All the Solutions

- Your problem may be in manufacturing but the ***solution could be somewhere else***

Where?

  - Designers and engineers
  - Purchasing
  - Customer specs, revisions, and delivery schedules
  - Suppliers

Who else?

- If the solution is somewhere else, get those people involved
- ***If you do not ask, they can not help you***
- If not, how can you work around the problem?

Devise an Automation Plan

Prioritize

- Now that you know **WHAT needs to be automated**, you have to figure out **HOW to make it happen**

- ***Prioritize in a way that***:

Saves the company the most time/money

Gets you the best value

Devise an Automation Plan

Plan for the Unexpected

- ***Do not expect things to go perfectly the first time***
- Do expect to **make multiple revisions** to your plan and allow time for changes / improvements
- Do have a **backup plan** in case of delays because you can not get equipment or resources at the scheduled time
- Do have a **plan for changes in deadlines**, especially if the deadline is moved up

Implement your plan

Implement Your Plan

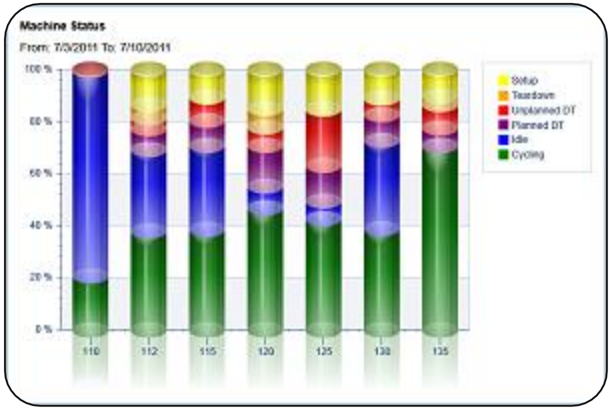
How CAM Can Help

- CAM **KnowledgeBase for storage** of your standards in a central database
- Expressions for **automatically calculating** machining values
- Visual Basic programs for **automatically performing** **functions** in CAM
- **Custom cycles** and **custom settings** for your specific machining requirements

Implement Your Plan

CAM Knowledgebase – Centralize Your Shop Floor Data

- **A central database that stores your standardized cutting tools, materials, speeds/feeds, machining preferences, machining processes**
  - Items in the database are available to anyone using CAM
  - Update your standards in one central location
  - Use security to prevent accidental updates or deletions
  - Transfer data between separate manufacturing locations
- **SQL database that stores:**
  - Cutting tool definitions
  - Speed and feed standards
  - Machining and cutting tool defaults
  - Families of parts
  - Machining processes



Implement Your Plan

CAM Knowledgebase – Choose Your Level of Automation

- **Easy**
  - Set up and store cutting tool definitions
  - Set up and store feeds/speeds, material classes/conditions
  - Set up and store machining preferences
- **Intermediate**
  - Set up and store part types and feature types unique to your business
  - Modify the standard machining processes to your own best practices
- **Advanced**
  - Automatically recognize features, associate machining processes, and apply those processes for complete tool path in minutes

Implement Your Plan

Expressions and the Expression Builder

- Short mathematical or VB commands entered directly into a field on a technology page
- Always start with = sign, then type the expression (=feature.depth/2)

Levels of automation

- **Easy**: Type expressions to calculate values used on a regular basis or to pick cutting tools based on the size of the feature
- **Intermediate**: Expression Builder gives you access to lists of ESPRIT variables, functions, and modules to build more complex expressions
- **Advanced**: Create your own rules with VB code

Implement Your Plan

The Post Mortem

- **A critical step you do not want to skip**
- **Get everyone together for a final review at the end of the project**
  - What went well?
  - What went wrong?
  - What could we have done better?
  - How do the results compare with our benchmark tests?
  - How can we do things better in the future?
- **This is a team effort**
- **Focus on constructive feedback and advice**
- **Do not let this degenerate into a gripe session**

Keep Improving

Keep Improving

Leverage Your Success

- Keep the **momentum** going!
- **Never stop looking** for processes to improve
- Always say **“We can do things better”**
- **Evaluate** your processes on a regular basis to keep them on track

Numerical Control (NC)

Numerical Control (NC)

- One of the most important developments in manufacturing automation is **Numerical Control (NC):**

"A Numerical Control machine is a machine positioned automatically along a pre-programmed path by means of coded instructions"

(Computer Numerical Control: Concepts & Programming, W. Seames, 2001)

- **Numerical Control (NC)** helps solve the problem of making **Manufacturing Systems** (**MFG**) more flexible

Numerical Control (NC)

NOTE

NC is a general term used for **N**umerical **C**ontrol

CNC refers specifically to **COMPUTER NUMERICAL CONTROL**

CNC machines are all NC machines

BUT

not all NC machines are CNC machines

The History of NC

The precursor technology

- The oldest form of data storage is generally considered to be in the form of punch cards, which date all the way back to **1725**
- First used by **Basile Bouchon** when working for **the textile industry**, he used a perforated paper loop to store patterns
- The first punch card tabulating and sorting machines that could record information were developed by **Herman Hollerith**, founder of the company that would become IBM, in the late 1880s

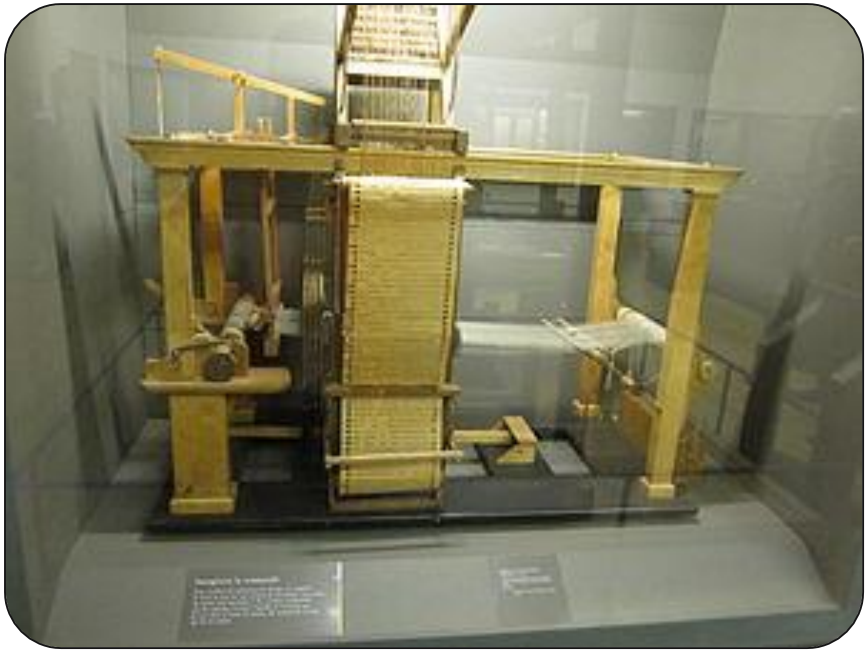


Figure :Basile Bouchon 1725 loom on display at the Musée des Arts et Métiers, Paris

(source: http://en.wikipedia.org/wiki/Basile_Bouchon)

(http://www.datacenterknowledge.com/archives/2012/09/14/tape-backup-60-anniversary/)

The History of NC

- **1947**: J. Parsons (Parsons Corporation) began experimenting for using **3-axis curvature data** to control machine tool motion for the production of aircraft components
- **1949**: Parsons awarded a US Air Force contract to build the first NC machine
- **1951**: MIT was involved in the project
  - **1952**: NC achieved when MIT demonstrated that simultaneous 3-axis movements were possible using a laboratory-build controller and a Cincinnati HYDROTEL vertical spindle
  - **1955**: after refinements NC become available to industry
  - **1959**: MIT announces Automatic Programmed Tools (APT) programming language

Innovation

HMI*

HMI*:stands for Human Machine Interface

NOTE

Innovation and **change** have always been **key components of any successful company**.

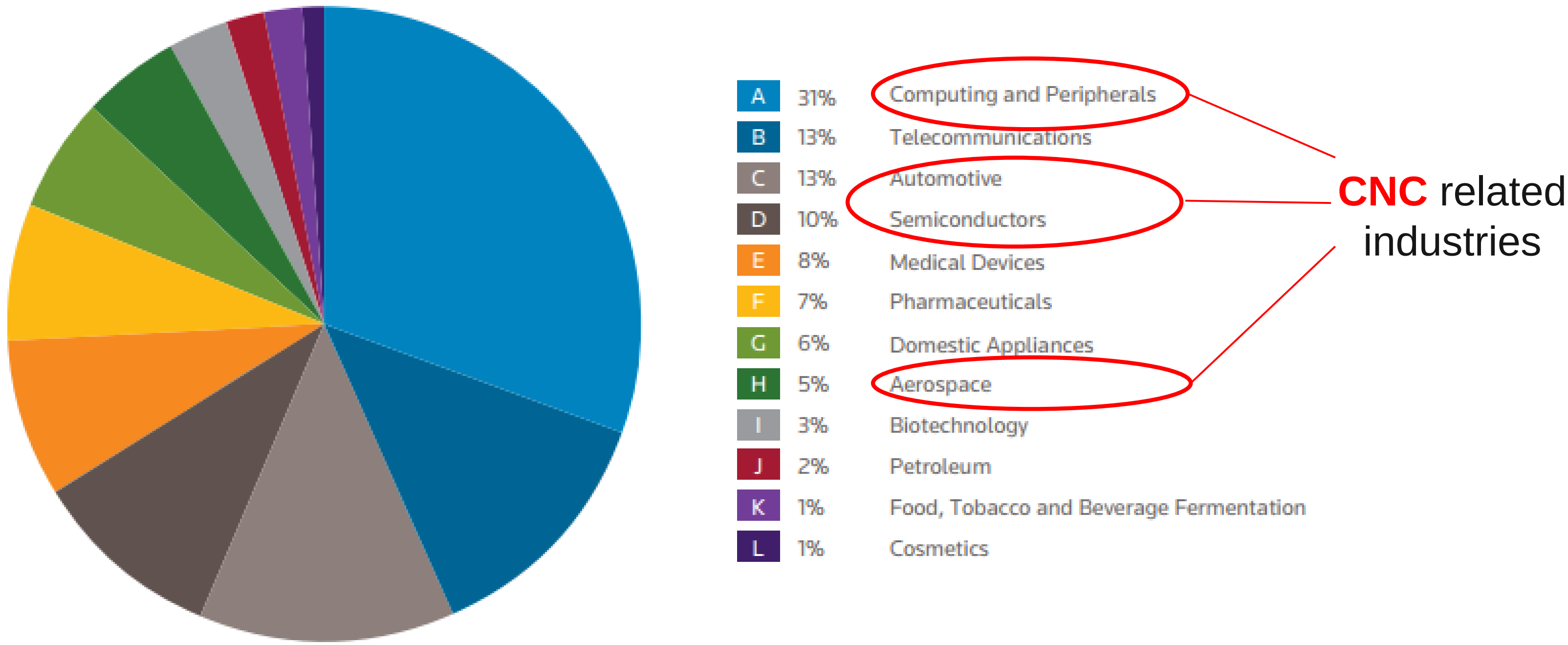
The History of NC

- **1960:** Direct Numerical Control (DNC) - Eliminates paper tape punch programs and allows programmers to send files directly to machine tools
- **1968**: Kearney & Trecker machine tool builders market first machining center
- **1970's**: CNC machine tools
- **1980's**: Graphics based CAM systems introduced - Unix and PC based systems available
- **1990's**: Price drop in CNC technology
- **1997**: PC Windows/NT based "Open Modular Architecture Control (OMAC)" systems introduced to replace "firmware" controllers
- **2001-2007**: Machine simulation, virtual prototyping and WEB services – Condition Monitoring via the Internet

Comment

2014 State of Innovation report

- You need to be different if not **ground-breaking** in order to get ahead



> *"Innovation is the process of turning ideas into manufacturable and marketable form."*
>
> *Watts Humphrey*
> *Influential Thinker in Software Engineering*

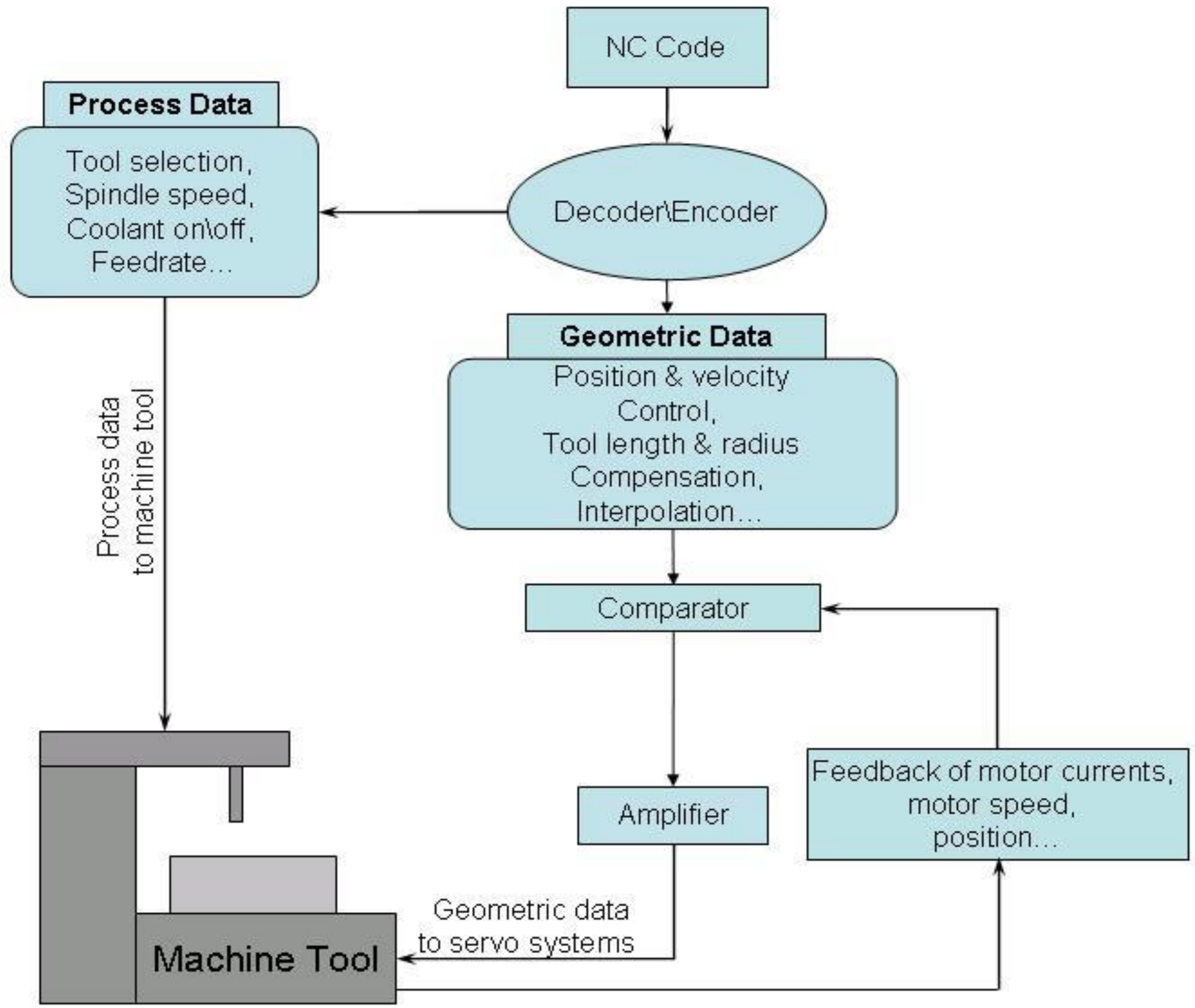
(http://blog.thomsonreuters.com/index.php/2012-state-of-innovation-report/)

Numerical Control (NC)

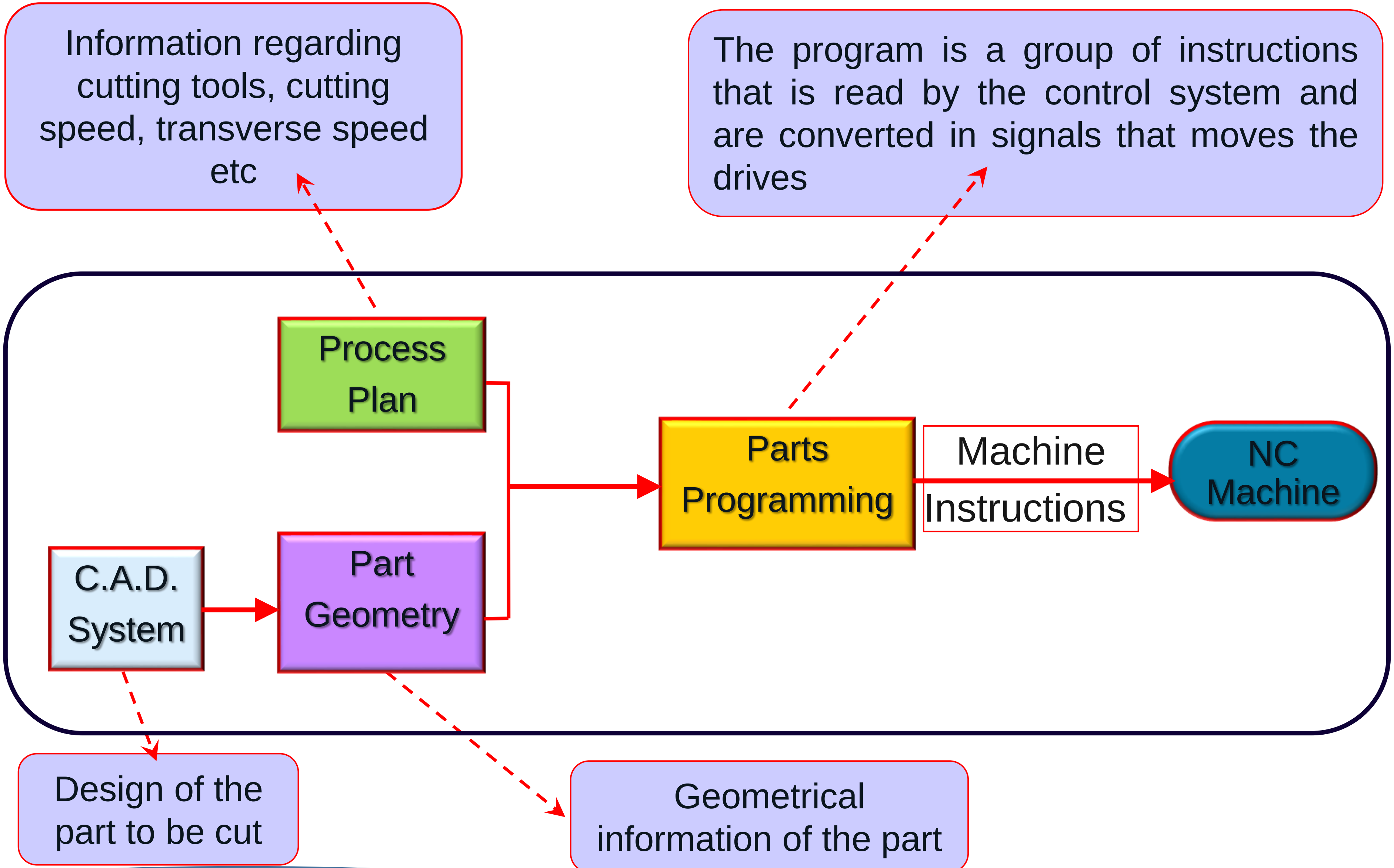
- ***Computer is used as the Control Unit (CU)*** of the modern Numerical Control machinery
- **Computer replaced the Tape Reader** found on earlier NC machines
- Program is loaded into and executed from the machine's computer

- **Computer Numerical Control (CNC)** machines are the NC machines of today
- **FOCUS on**: **M**anual **D**ata **I**nput **(MDI)** programming of CNC machinery

Functions of Numerical Control



Process of Producing a Part Program (NC Code)



Programming CNC Machine Tools

Part Programming

Manual Part Programming

Computer-assisted Part Programming

The NC program is entered directly into the NC code editor by the machine operator or part programmer.

A programming software reads the geometry made by a C.A.D. software and generates automatically the NC program

Programming languages

- APT
- ADAPT
- AUTOSPOT
- G-code

Programming CNC Machine Tools

The **NC codes** can be broadly classified into **two groups**

Commands for controlling individual machine components

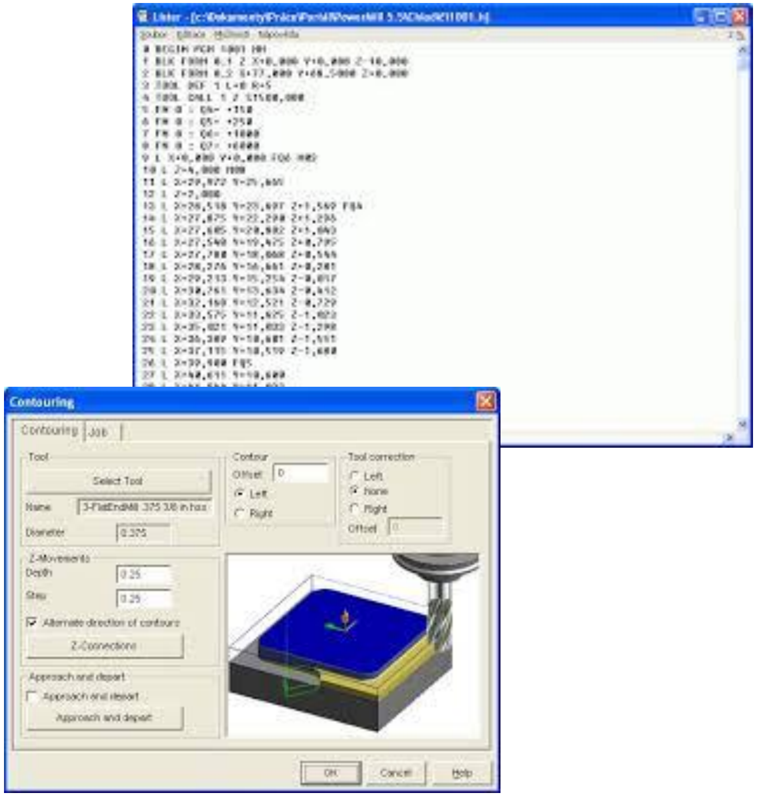
- Motor on/off control
- Spindle speed
- Tool change
- Coolant on/off
- …

Commands for controlling the relative movement of the workpiece and the tools

- Position/Velocity control
- Tool length/Radius compensation
- Interpolation
- …

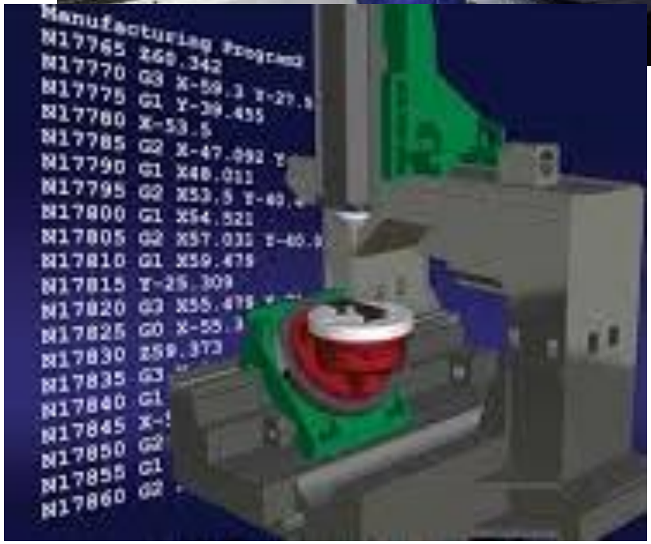
NC Definition, it's Concepts And Advantages

- **Numerical control (NC)** has been used in industry **for more than 40 years**
- **NC** is a method of automatically operating a manufacturing machine based on a **code of letters, numbers, and special characters**
- *A complete* **set of coded instructions** for executing an operation is **called a program**
- The program is translated into corresponding ***electrical signals for input to motors that run the machine***



NC Definition, it’s Concepts And Advantages

- Numerical controlled machines can be **programmed manually**
- If a computer is used to create a program, the process is known as **computer-aided programming**
- The approach we take is in the form of **Manual Programming**



NC Definition, it's Concepts And Advantages

Numerical control (NC) was developed with these goals in mind:

I. To **increase production**

II. To **reduce labor costs**

III. To make **production more economical**

IV. To do **jobs** that would be impossible or **impractical without NC**

V. To **increase the accuracy** of duplicate parts

Before deciding to utilize an NC or CNC machine for a particular job the requirements and economics must be weighted against the advantages and disadvantages of the machinery

NC Definition, it's Concepts And Advantages

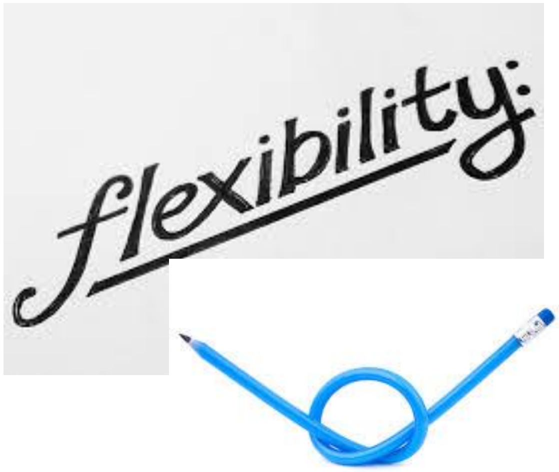
Advantages

- Increased **productivity**
- Reduced tool/fixture **storage and cost**
- **New functions** can be programmed into the MCU as software
- **Less hardware**
- Many **different CNC programs can be stored in the MCU**
- **Faster setup time**
- **Reduced parts inventory**

NC Definition, it's Concepts And Advantages

More Advantages

- **Flexibility** that speeds changes in design
- Better **accuracy** of parts
- **Reduction in parts handling**
- Better **uniformity** of parts
- Better **quality** control
- **Improvement in manufacturing control**
- Several DNC can be networked forming a **large distributive NC system**



NC Definition, it's Concepts And Advantages

Disadvantages

- Increase in **electrical maintenance**
- High **initial investment**
- Higher per-hour **operating cost** than traditional machine tools
- **Retraining** of existing personnel

Applications in Industry

- Originally developed for use in **Textile industries**
- Widespread nowadays in the following manufacturing industries:
  - Aerospace
  - Defence
  - Automotive
  - Electronic
  - Appliance
  - Tooling industries
- Advances in microelectronics have **lowered the cost** of acquiring CNC equipment
- ***Bending, Forming, Stamping, Inspection machines and machines used for material removal processes*** have been produced as NC systems

Evolution of NC Machines

- Early NC machines run off **punched cards** and **tape**
- Due to the **time and effort** for editing and changing tapes **Computers** where introduced for programming

Computers' Involvement

Computer Aided Programming Languages

Direct Numerical Control

Evolution of NC Machines

Traditionally, NC systems have been composed of the following components:

- **Tape punch*:*** converts written instructions into a corresponding hole pattern
- The hole pattern is punched into tape, which passes through this device
- Much older units used a **typewriter device** called a **Flexowriter**
- Later devices included a **microcomputer coupled with a tape punch unit**
- **Tape reader*:*** reads the hole pattern on the tape and converts the pattern to a corresponding electrical signal code
- **Controller*:*** receives the electrical signal code from the tape reader and subsequently causes the NC machine to respond

Input Media

Punched Tape

- The oldest medium for program storage
- Made from **paper** or **Mylar plastic** (stronger than paper)
- The NC program code is **entered into the tape** by tape puncher in a **form of a series of holes** representing the NC codes
- A **tape reader** by electrical, optical or mechanical means ***senses the holes and transfers the coded information into the machine computer***
- The NC code is entered into **CAM** or Word Processor program and punched into tape

Binary Numbers

How controller processes information?

- It is important in learning to program CNC machinery
- Computers and Computer- Controlled machinery **do not deal** in Arabic symbols or numbers
- All of the internal processing is done by calculating or comparing **binary** numbers
- **Binary** numbers contain only two digits: **ZERO (0)** and **ONE (1)**
- Within CNC controller:
  - Each **binary digit "1"** may represent a **"positive charge" or**
  - A **binary digit "0"** may represent a **"negative charge"** or
  - A **"1"** may be the **"ON"** or
  - A **"0"** may be the **"OFF"**

Binary Numbers

ARABIC	BINARY	ARABIC	BINARY
0	0	18	10010
1	1	19	10011
2	10	20	10100
3	11	21	10101
4	100	22	10110
5	101	23	10111
6	110	24	11000
7	111	25	11001
8	1000	26	11010
9	1001	27	11011
10	1010	28	11100
11	1011	29	11101
12	1100	30	11110
13	1101	31	11111
14	1110	32	100000
15	1111	64	1000000
16	10000	128	10000000
17	10001		

Figure 1-2: Binary Numbers Compared To Arabic Numbers

- The CNC program code in binary form must be loaded into the computer
- Programming formats and **languages allow the NC code to be written using alphabetic characters** / base-ten decimal numbers
- When the **NC program** is punched or recorded on tape or other storage media the information is **translated to binary form**

Tape Formats

- Today **punched tape is not often used** for NC program storage
- Formats used in NC programming are still referred as **Tape Formats**
- Computer files containing the NC programs are referred as **"tape files"**, **"punch files"** or **"tape image files"**
- Old machinery is still used in machine shops

RS-274 Format

- Follows **E**lectronics **I**ndustries **A**ssociation **(EIA**) standard
- **Program information** is contained in program lines called **"Blocks"**
- **"Blocks"** are punched into the tape in one or two tape code standards
- **RS-274** is a **"variable block coding"** format
- The information contained in a block may be arranged in any order

Tape Formats

RS-244 Binary Coded Decimal (BCD)

- The **EIA RS-244** standard is one of the two tape codes used for NC tapes
- Became a standard early in the development of NC – limited punctuation
- Each **hole** represents the digit **“1”** while each **blank** the digit **“0”**
- The tape code allows alphabetic characters and base-ten numbers to be translated into the binary code the controller requires (**B**inary **C**oded **D**ecimal – BDC)

RS-358 Format

- Government, telephone and Computer industries required tape code containing upper and lower case letters
- The existing tape coding formats were sufficient only for machining
- The standard accepted was **A**merican **S**tandard **C**ode for **I**nformation **I**nterchange (ASCII)
- **EIA RS-358** was adopted
- **EIA RS-358** is also as ISO and ASCII is a subset of the ASCII code used in other applications – Today is dominant over RS-244

Tape Formats

TRACK NUMBER

8	7	6	5	4		3	2	1	
		●			•				0
					•			●	1
					•		●		2
			●		•		●	●	3
					•	●			4
			●	●	•			●	5
			●	●	•		●		6
					•	●	●	●	7
				●	•				8
			●	●	•			●	9
	●	●			•			●	a
	●	●			•		●		b
	●	●	●		•		●	●	c
	●	●			•	●			d
	●	●	●		•	●		●	e
	●	●	●		•	●	●		f
	●	●			•	●	●	●	g
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		●	●	●	•				y
		●		●	•			●	z
	●	●		●	•		●	●	. (Period)
		●	●	●	•		●	●	, (Comma)
		●	●		•			●	/
	●	●	●		•				+
	●				•				-
			●		•				Space
	●	●	●	●	•	●	●	●	Delete
●									CARR. RET. (EOB)
		●		●	•		●		Back Space
		●	●	●	•	●	●		Tab
				●	•		●	●	End of Record
					•				Tape Feed Hole
									Blank Tape

● = Hole in Tape
• = Tape Feed Hole

TRACK NUMBER

8	7	6	5	4		3	2	1	
		●	●		•				0
●		●	●		•			●	1
●		●	●		•		●		2
		●	●		•		●	●	3
●		●	●		•	●			4
		●	●		•	●		●	5
		●	●		•	●	●		6
●		●	●		•	●	●	●	7
●		●	●	●	•				8
		●	●	●	•		●		9
	●				•			●	A
	●				•		●		B
●	●				•		●	●	C
	●				•	●			D
●	●				•	●		●	E
●	●				•	●	●		F
	●				•	●	●	●	G
	●			●	•				H
●	●			●	•			●	I
●	●			●	•		●		J
	●			●	•		●	●	K
●	●			●	•	●			L
	●			●	•	●		●	M
	●			●	•	●	●		N
●	●			●	•	●	●	●	O
	●		●		•				P
●	●		●		•			●	Q
●	●		●		•		●		R
	●		●		•	●	●		S
●	●		●		•	●			T
	●		●		•	●		●	U
	●		●		•	●	●		V
●	●		●		•	●	●	●	W
●	●		●	●	•				X
	●		●	●	•			●	Y
	●		●	●	•		●		Z
●	●	●	●	●	•	●	●	●	Delete
●				●	•				Back Space
				●	•		●		Horiz. Tab
				●	•	●			Line Feed
●				●	•	●		●	Carr. Ret. (EOB)
●		●			•				Space
●		●			•	●		●	%
		●		●	•				((Open Paren.)
●		●		●	•			●	) (Close Paren.)
		●		●	•		●	●	+
		●		●	•	●		●	—
●		●		●	•	●	●	●	/
		●	●	●	•		●		: (Colon)
					•				Tape Feed Hole
									Virgin Tape

● = Hole in Tape
• = Tape Feed Hole

Figure 1-3: EIA RS-244 tape code

(Seams W., “Computer Numerical Control, Concepts & Programming,4th edition)

Computer Numerical Control (CNC)

Definition of CNC and Its Components

- A **Computer Numerical Control** (**CNC**) machine is an NC machine with the **added feature of an on-board computer**

- The **on-board computer** is often referred to as the **Machine Control Unit** (**MCU)**

- **Control units** for NC machines are usually **hard wired**. This means that all machine ***functions are controlled by the physical electronic elements*** that are built into the controller

- The on-board computer, on the other hand, **is "soft" wired**

Definition of CNC and Its Components

- Thus, the **machine functions are encoded into the computer** at the time of manufacture

- They **will not be erased** when the CNC machine is **turned off**

- Computer memory that holds such information is known as **ROM** (**R**ead-**O**nly **M**emory)

- The **MCU** usually has an alphanumeric keyboard for **direct or manual data input** (**MDI**) of part programs.

- Such programs are stored in **RAM** or the random-access memory portion of the computer

Definition of CNC and Its Components

- Programs can be **played back**, **edited**, and **processed** by the control. All programs residing in **RAM**, however, **are lost** when the CNC machine is **turned off**

- These programs can be **saved on auxiliary storage devices** such as punched tape, magnetic tape, or magnetic disk

- Newer **MCU** units have **graphics screens that can display** not only the CNC program but the **cutter paths** generated and any errors in the program

- The **components** found in many CNC systems are shown in Figure **1-4(a)**

Definition of CNC and Its Components

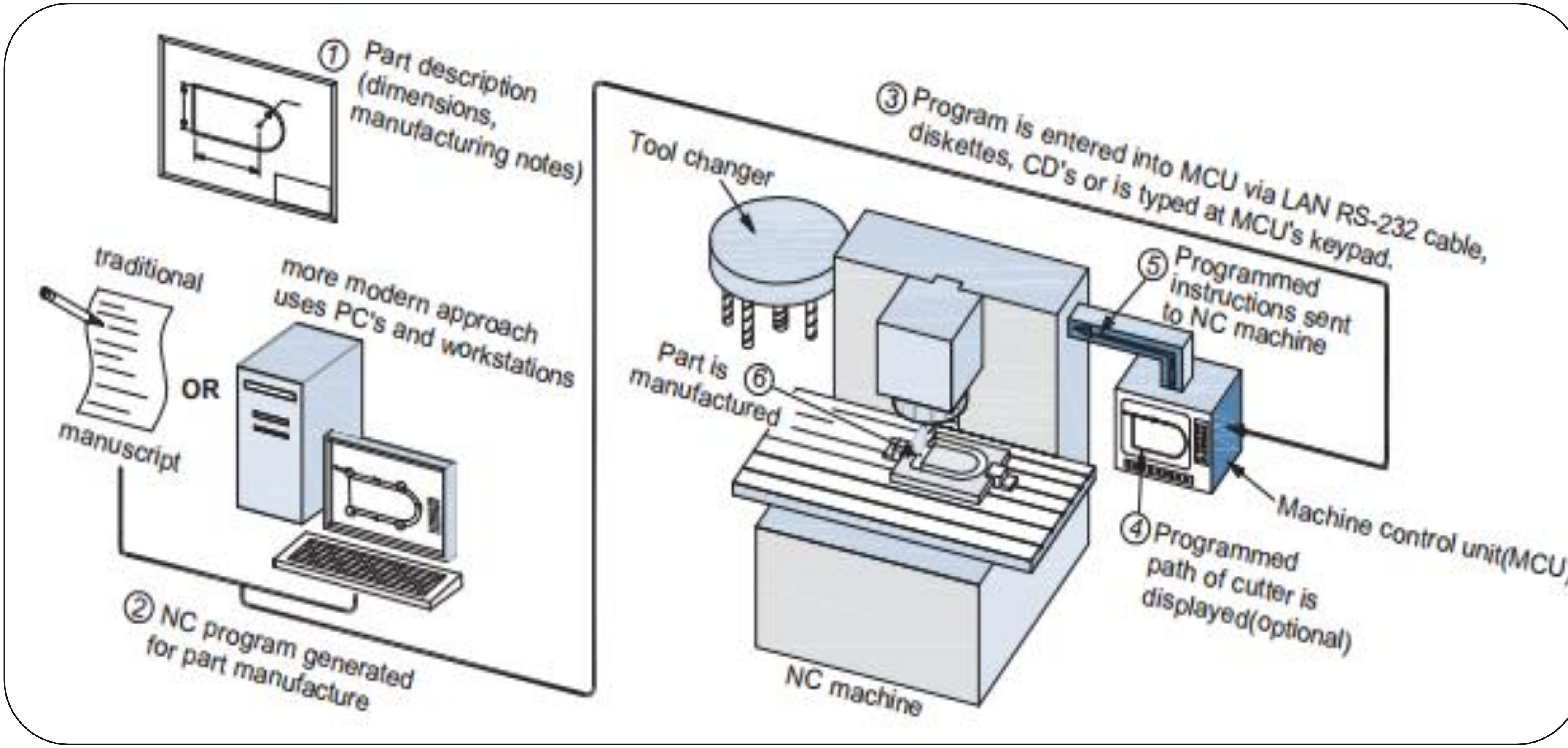


Figure 1-4(a) :Components of Modern CNC Systems

(Introduction to Computer Numerical Control, 4th Edition, J.V. Valentino, E.V. Goldenberg, 2007)

Machine control unit

- **Generates**, **stores**, and **processes** CNC programs
- Also **contains the machine motion controller** in the form of an executive software program as shown in Figure 1-4(a)

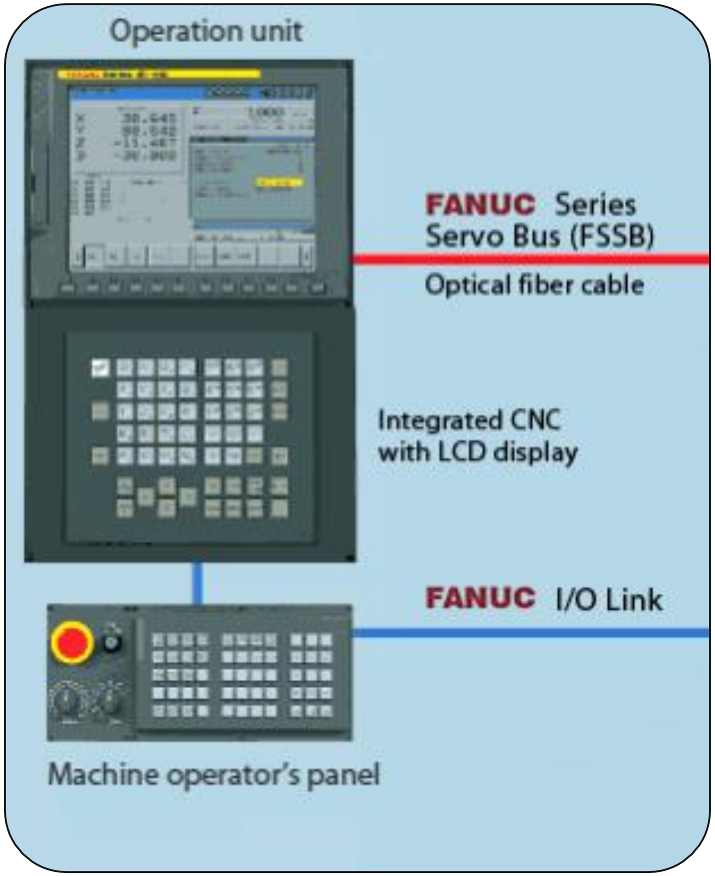


Figure 1-4(b): FANUC Series 0*i* Mate

(source: http://www.fourstarcnc.com/?f=PrecisionAccessories)

CNC Components

NC machine:

- **Responds to programmed signals** from the machine control unit and manufactures the part

- Accordingly, **executes the required motions to manufacture a part**

- Motions may be: **spindle rotation on/off**, **table and or spindle movement along programmed axis directions**, etc.

CNC Machines

CNC machine:

- A CNC machine has **more programmable features** than older NC tape machinery

- A CNC machine may be used as stand-alone unit in a network of machines – **Flexible Machining Centers** or **Machining Cells**

- CNC machines are **easier to program** by **more than one method:**

  - On board computer keyboard
  - Electronic connector to transfer a program to CNC machine

A CNC machine is a soft-wired controller

- Once the CNC program is **loaded** into the computer's memory **no HW is required to transfer the NC codes to the controller**
- The controller uses a **permanent resident program** – **EXECUTIVE PROGRAM** – to **process the codes into electrical pulses** to control the machine
- **EXECUTIVE Program** is called "**executive software**" or "**executive firmware**"

EXECUTIVE program resides in **ROM** (**R**ead **O**nly **M**emory)

NC code resides in **RAM** (**R**andom **A**ccess **M**emory)

Firmware: Routines of SW including low-level instructions stored in ROM only for reading

(Seams W., "Computer Numerical Control, Concepts & Programming,4th edition)

CNC Machines

ROM (Read Only Memory)

- Is an **electronic chip** which can be accessed by a computer but not altered (erased or written) without special equipment
- The **EXECUTIVE** program **can not be erased**
- The **EXECUTIVE** program **is always active** when machine is on

RAM (Random Access Memory)

- **RAM** can be altered by the computer
- NC code is written into **RAM** by keyboard or other outside source
- The content of **RAM** is lost when the controller is turned off
  - **Battery backup system** is used for **saving the program in the event of power loss**
  - **CMOS** (**C**omplementary **M**etal–**O**xide–**S**emiconductor) memory special type of **RAM** which **retains the information content in the case of power loss**

CNC Machines

Examples of CNC Machines

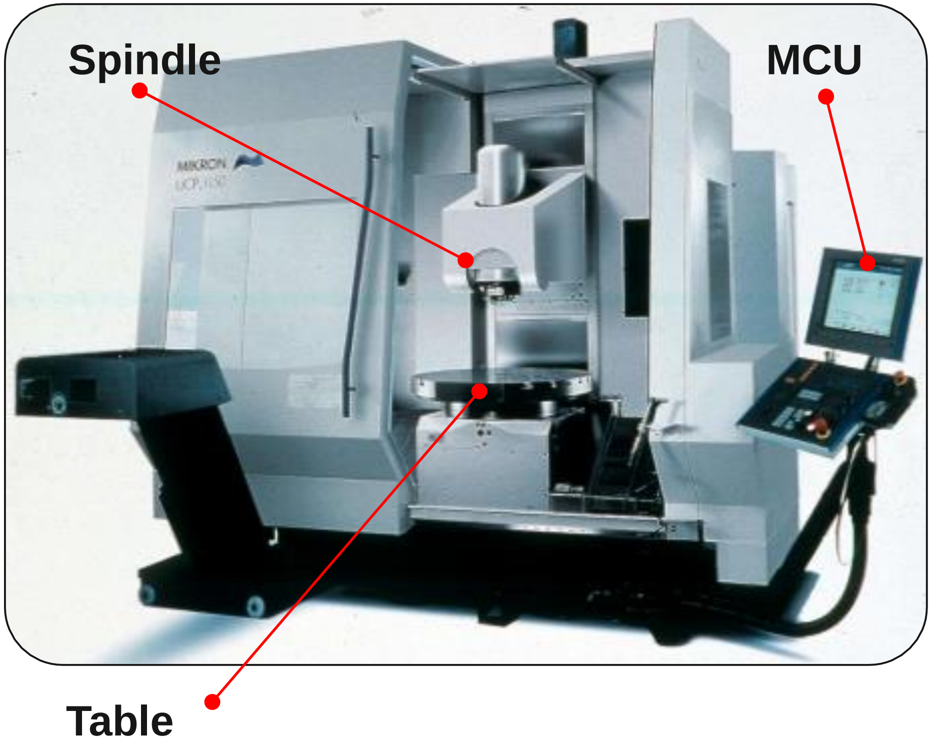


Figure 1-5: MICRON UCP 1150,5-axis vertical machining center
(http://www.mikron.com/)

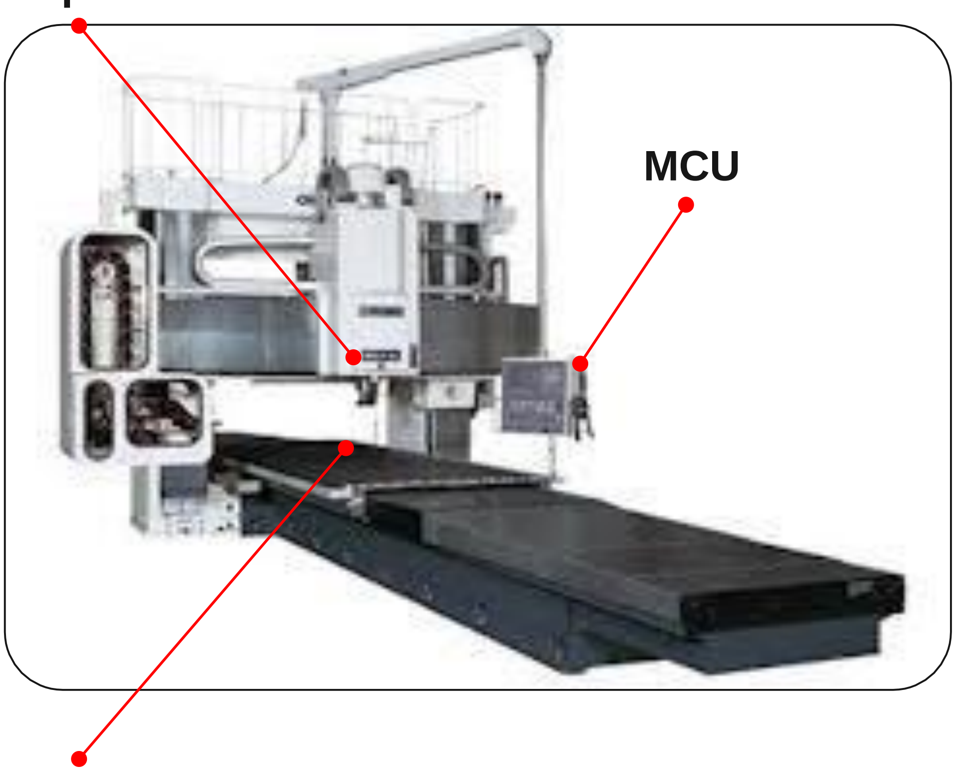
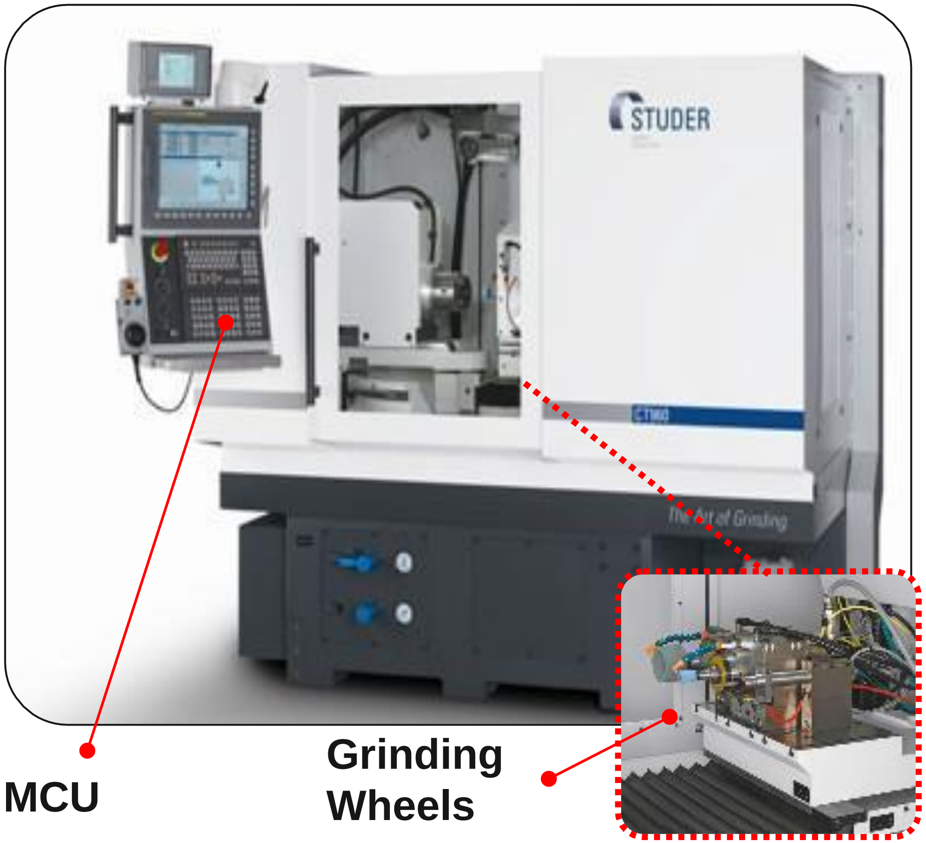


Figure 1-6 :OKUMA MCR-A5C 3 axis machining center
(http://www.okuma.com/)

CNC Machines

Examples of CNC Machines



MCU

Grinding Wheels

Turret

Slant Bed

MCU

Figure 1-7:STUDER CT930, 5 axis CNC cylindrical grinding machine(http://www.studer.com)

Figure 1-8 :Haas TL-15 CNC Lathe (http://int.haascnc.com)

Direct Numerical Control

Computer Aided Programming Languages:

- Allow the development of an NC program using a set of universal "pidgin English" commands

- Computer translate **commands** into **machine codes**

- Machine codes are punched into the tapes

Direct Numerical Control:

- A computer is used as a **partial or complete controller** of one or more NC machines

Direct Numerical Control

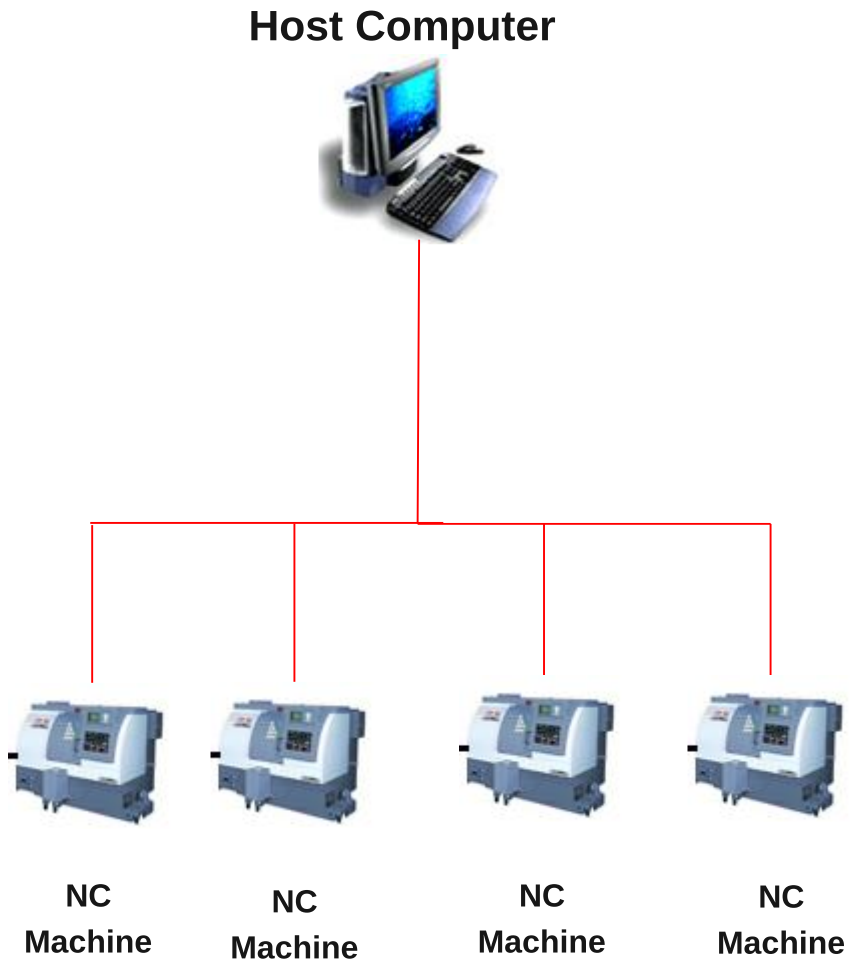


Figure 1-9: Direct numerical control
(adapted from Seams W., "Computer Numerical Control, Concepts & Programming,4th edition)

Direct Numerical Control:

- Expensive mainframe or mini-computers were required in the past
- Due to cost the use of DNC was limited to large companies
- Powerful PCs given rise to affordable PC-based DNC systems
- Most of PC-based DNC systems running on MS Windows OS

Distributed Numerical Control

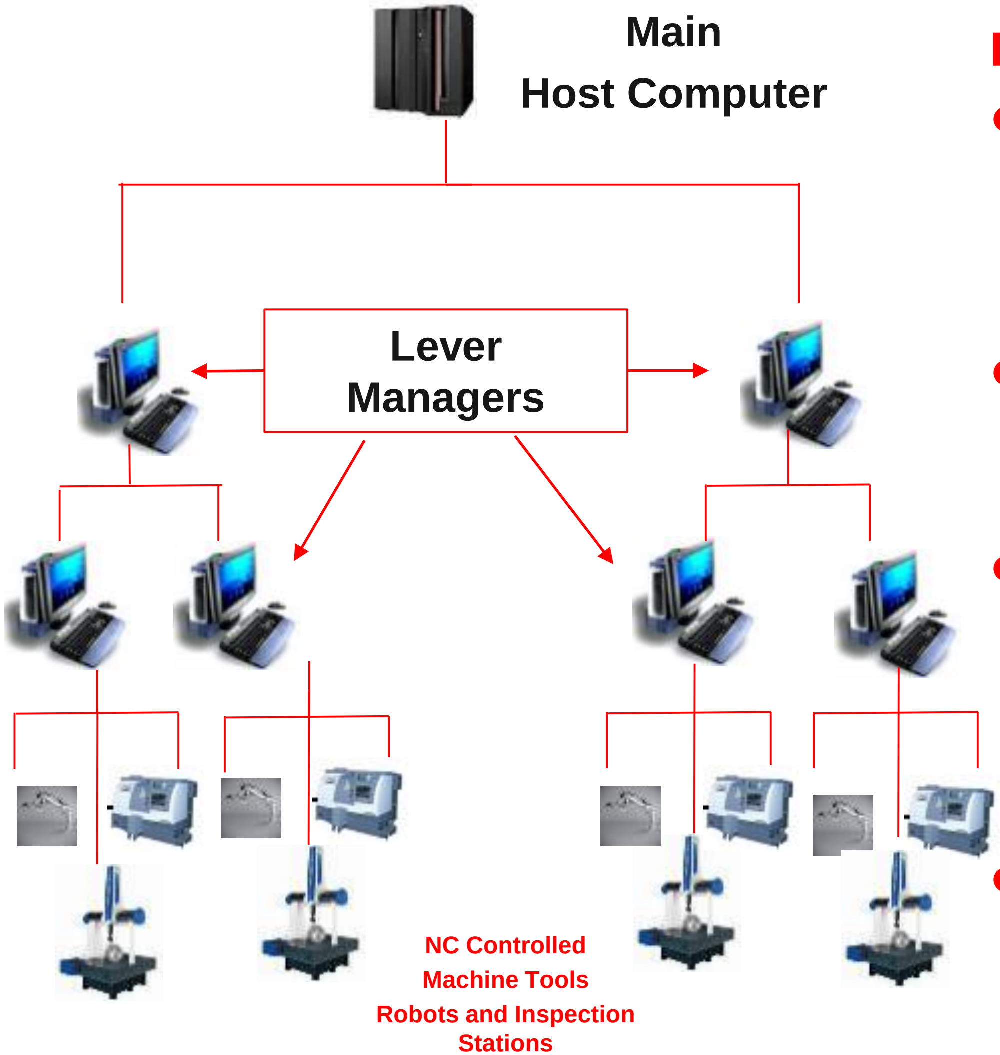


Figure 1-10: Distributed numerical control

(adapted from Seams W., "Computer Numerical Control, Concepts & Programming,4th edition)

Distributed Numerical Control:

- A network of computers is used to coordinate the operation of a number of CNC machines
- Ultimately an **entire factory** can be coordinated in this manner
- **Alternative System 1**: NC program is transferred in its entirety from a host computer directly to machines controller
- **Alternative System 2**: NC program is transferred from a mainframe or a host computer to a PC on the Shop Floor, stored and used when needed → transferred to machine controller

Programming Methods

- For **language-type programming**, **APT**, **EXAPT**, **FAPT**, **KAPT**, and **COMPACT II** have been widely used

- **Automatically Programmed Tools (APT)**
  - A text based system in which a programmer defines a series of lines, arcs, and points which define the overall part geometry locations
  - These features are then used to generate a cutter location (CL) file

- **Programming Methods- APT**
  - Developed as a joint effort between the aerospace industry, MIT, and the US Air force
  - Still used today and accounts for about 5 -10% of all programming in the defense and aerospace industries

(Overview to Computer Aided Manufacturing - ENGR-2963 - Fall 2005 S. Chiappone)

Programming Methods

APT

- Was developed in the USA in the 1960s, is the **most famous system** for the language-type programming tool and has **the greatest number of functions**
- The part program consists basically of four parts:

1) The **shape definition part** where the shape for the machined part is specified

2) The **motion definition part** where the tool paths are specified

3) The **post processor part** where cutting conditions and the characteristics of the CNC system are specified

4) The **Auxiliary part** where auxiliary data such as tool size, workpiece number, and so on is specified

(Theory and Design of CNC Systems ,S.H. Suh,2008)

Programming Methods

APT

Part definition Example

P1=Point/12,20,0	Point definition=(x, y, z coordinates)
C1=Circle/Center,P1,Radius,3	Circle definition=(center coordinates, Radius)
LN1=Line/C1. ATANGL,90	Line definition=(angle that is shaped when intersecting a specific point)

Program Example

C1=CIRCLE/0,0,0,1	create a circle centered at 0,0,0 ,radius 1
L1=LINE/XAXIS	create a line on the xaxis
CUTTER/0.25	define a tool
FROM/0,0,0	start point of the tool
INDIRV/0,1,0	direction the tool initially moves
GO/TO,C1	direct the motion of the tool to c1
FINI	end of program

(http://aptos.sourceforge.net/WhatisApt.html)

Programming Methods

EXAPT

- **EXAPT** was developed in Germany. There are three kinds of **EXAPT**; **EXAPT I for position control and linear machining, EXAPT II for turning**, and **EXAPT III for milling** such as two-dimensional contour machining and one-Dimensional linear machining. **EXAPT** is very **similar** to **APT** but without workshop technology

- **EXAPT** decides automatically **how many tools are needed** by considering the material of the workpiece, required surface roughness, and the shape of the hole specified by the programmer

- **It calculates automatically the spindle speed and feedrate**. In **EXAPT II**, with user specification of the shape of the blank material and machined part, all machining operations including the machining allowances are generated automatically

(Theory and Design of CNC Systems ,S.H. Suh,2008)

EXAPT

- On the other hand, it is necessary to **register the pre-specified data** because appropriate spindle speed, feed-rate, and cutting depth can be varied according to the machine and tools

- Because **EXAPT generates automatically not only the tool path but also machining operations and cutting conditions**, it is easier to use than **APT**

- However, the kinds of machineable part shape that can be handled are more limited than with **APT**

Programming Methods

FAPT

- **FAPT** was developed by FANUC and is similar to **APT**
- **FAPT** can be used in carry-on exclusive programming equipment. By using particular programming software such as **FAPT Turn**, **FAPT Mill**, and **FAPT DIE-II**, part programs for turning, milling, and die and mold machining can be generated easily
- The **FAPT Turn/Mill** system has the following characteristics
- **FAPT turn** is a software library for turning
- For part programming, the coordinate system of the rotation axis of the workpiece is defined as the Z-axis and the radius direction of the workpiece is defined as the X-axis

Programming Methods

FAPT

- It is possible to **program based on both diameter and radius values** of the X-axis. **FAPT turn** provides:

  1. Roughing
  2. Finishing
  3. Grooving and
  4. Threading as metal-removal operations

- The tool nose compensation such as leaving finish allowance based on the machining tolerance and tool radius is possible

- In addition, the **tool path can be displayed graphically**

Programming Methods

FAPT

- **FAPT Mill** is the automatic programming system for generating a part program for milling
  - It supports **drilling, 2.5D machining** of shapes made from lines and arcs, **3D machining** of shapes made from spheres, cylinders, cones, and slanted planes
  - **Free-form curves made using discrete points and pattern drilling**, which is a repetition along a pattern element such as a line, arc, or grid, are possible
  - During simulation, the **tool path can be displayed** on the XY plane, YZ plane, ZX plane, or on an arbitrary plane projected from an arbitrary direction

Programming Methods

FAPT

- In **FAPT Mill**:

  1. It is possible to **define a variety of geometries** based on point, line, arc, slant plane, cylinder, cone, and sphere
  2. It is not necessary to define extra geometries for generating desired shapes
  3. It is possible to **specify tool movement** with a descriptive geometry name
  4. Tool radius compensation (left/right) and subroutine calls are possible
  5. Variables and a variety of mathematical functions, such as the four arithmetical operations and trigonometric functions, can be used

FAPT

- Apart from these, other programming languages, such as **COMPACT-II**, have been developed

- However, the **basic concept of these is similar to that of APT**

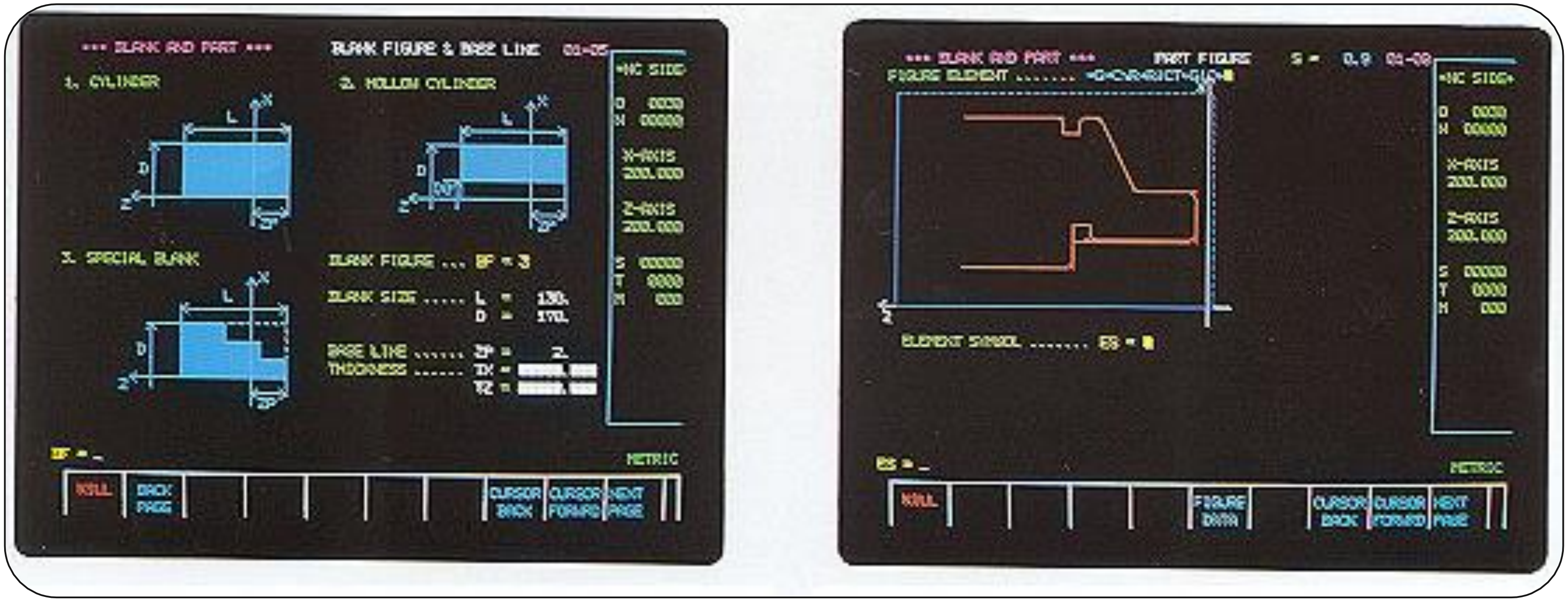
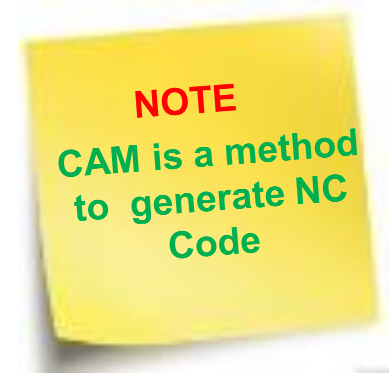


Figure1-11 :FAPT Programming

(Source: http://www.practicalmachinist.com)

Programming Methods

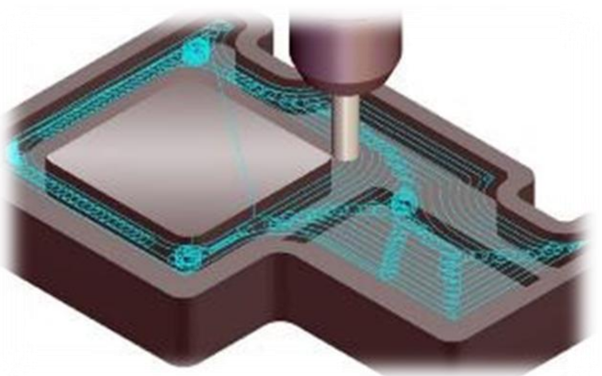
Computer Aided Machining (CAM) Systems



- **Graphic representation of the part**
- PC based
- Integrated **CAD/CAM** functionality
- “Some” **built-in expertise**
    - **Speed** & **feed data** based on material and tool specifications
- Tool & material libraries
- Tool path **simulation, editing , optimization**
- Tool path Cut time **calculations** for cost estimating
- Import / export capabilities to other systems

  Examples: Drawing Exchange Format (DXF)

  Initial Graphics Exchange Standard (IGES)



The Process CAD to NC File

Import File

DXF
IGES

- Geometry
  - Direct Input

- Tool Path Generation
  - What you want to cut
  - How you want to cut
    - Tool type
    - Rpm's-Feeds
    - Method
      - Canned cycles
      - Cut direction

CL File

Post Process

NC Code
N1 G80 G90
N2 G0 T01 M06
N3 G0 X0 Y0

OEM
Custom
Language

(Overview to Computer Aided Manufacturing - ENGR-2963 - 2005 S. Chiappone)

Programming Methods

The Process CAD to NC File

- **Start with graphic representation of part**

    i. Direct input

    ii. Import from external system (Example :DXF / IGES)

    iii. 2D or 3D scan (Model or Blueprint)

NOTE

(At this point you have a graphics file of your geometry)

(Overview to Computer Aided Manufacturing - ENGR-2963 - 2005 S. Chiappone)

The Process CAD to NC File

- **Define cutter path by selecting geometry**

  i. Contours
  ii. Pockets
  iii. Hole patterns
  iv. Surfaces
  v. Volume to be removed

NOTE **(At this point the system knows what you want to cut)**

- **Define cut parameters**

  i. Tool information (Type, Rpm, Feed)
  ii. Cut method (Example - Pocket mill zig-zag, spiral, inside-out)
  iii. Rough and finish parameters

NOTE **(At this point the system knows how you want to cut the part)**

The Process CAD to NC File

- **Execute cutter simulation**
  1. Visual representation of cutter motion

- **Modify / delete cutter sequences**

(At this point the system has a "generic" cutter location (CL) file of the cut paths)

- **Post Processing**
  1. CL file to machine specific NC code

- **Filters CL information and formats it into NC code based on machine specific parameters**
  1. Work envelope
  2. Limits - feed rates, tool changer, rpm's, etc.
  3. G & M function capabilities

Output: NC Code

- **Numerical Control (NC) Language**
  - A **series of commands** which “direct” the cutter motion and support systems of the machine tool
  - **G-Codes** (G00, G1, G02, G81)
  - **Coordinate data** (X,Y,Z)
  - **Feed Function** (F)
  - **Miscellaneous functions** (M13)
  - **N** - Program sequence number
  - **T** - Tool call
  - **S** - Spindle command

Output: NC Code

NC Simple Program Example

N05 G90 G20	(Absolute programming & Inches)
N10 S6000 M03	(Spindle On, 6000 RPM)
N15 G00 Z0.25	(Rapid Move)
N20 X0.0 Y0.85	(Rapid Move)
N25 G01 Z-.125 F20.	(Linear Move, Feedrate)
N30 X0.51 Y-0.68	(Linear Move)
N35 X-0.81 Y0.26	(Linear Move)
N40 X0.81 Y0.26	(Linear Move)
N45 X-0.51 Y-0.68	(Linear Move)
N50 X0.0 Y0.85	(Linear Move)
N55 G00 Z0.25	(Rapid Move)
N60 M05	(Spindle Off)
N65 M30	(End Program)

(http://www.teachstemnow.com/cnc-programming-101/)

Input Media

Input Media for the NC code into the Controller

- Are used to electronically or mechanically store the NC programs
- An NC program is read from the input medium when it is loaded into the machine
- Old NC machinery could **only read programs from punched tape** or DNC
- CNC machines may process **multiple means** of program input

Input Methods

Manual Part Programming: Manual programming of the machines

Computer Aided Programming (CAP): Programming done by a computer

Manual Data Input (MDI): A manual program is entered into the machine's controller via its own keyboard

Input Media

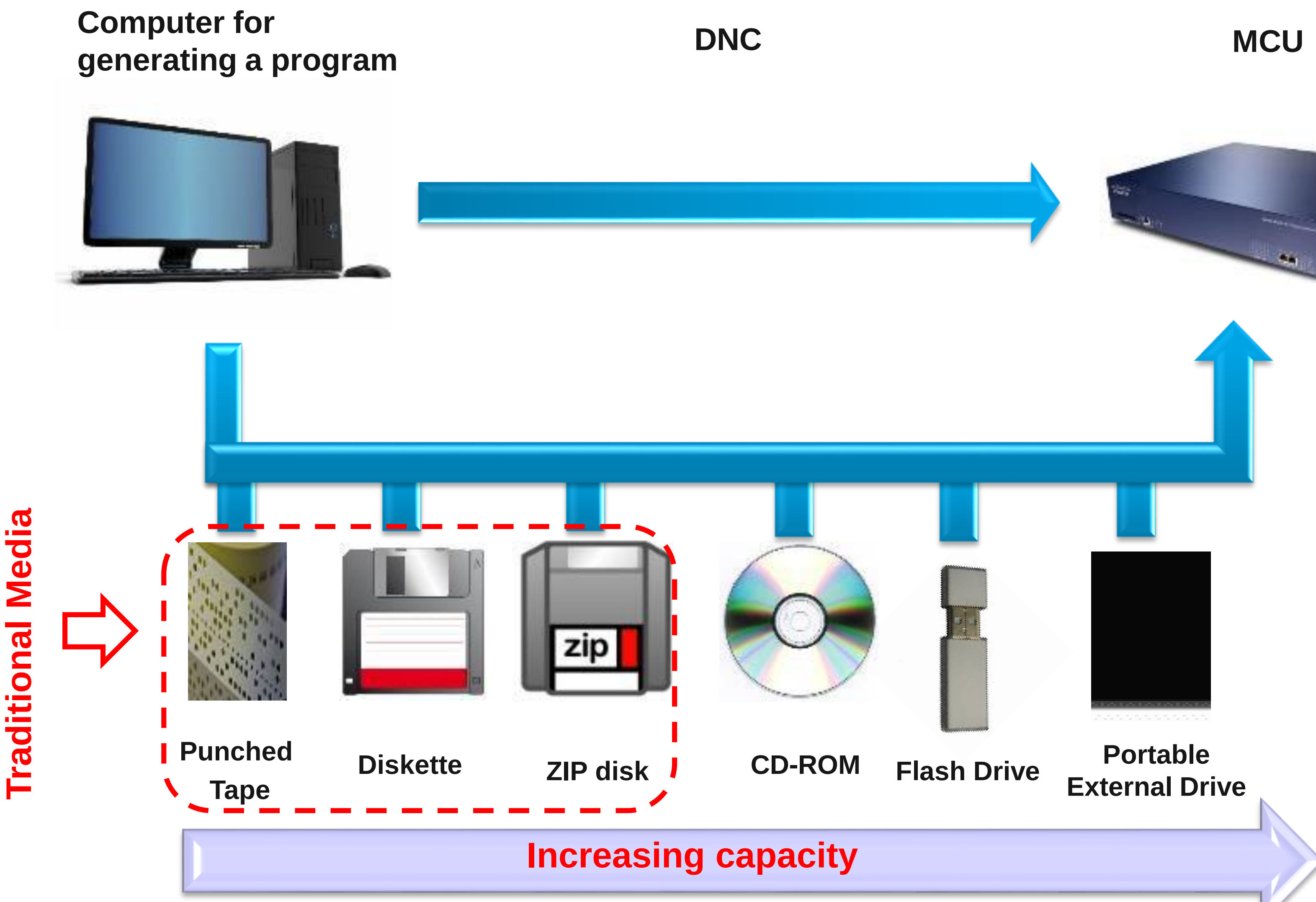


Figure 1-15:Traditional and modern CNC input and storage methods

(adapted from Seams W., “Computer Numerical Control, Concepts & Programming,4th edition)

Input & Storage Media

- The **advantages** of using flash devices instead of CDs or external hard drives are listed as follows:

  - **No fragile moving parts** that can break if dropped
  - Far **smaller in size**
  - **Do not require time-consuming configuration** to connect to the computer
  - **USB ports** are more **common** than CD or DVD burners
  - **Flash devices** are **automatically re-writable** and do not require a special drive

Special Requirements For Utilizing CNC

Computer numerical control machines can dramatically boost productivity. The CNC manager, however, can only ensure such gains by first addressing several critical issues

(Introduction to Computer Numerical Control, 4th Edition, J.V. Valentino, E.V. Goldenberg, 2007)

1. Sufficient **capital** must be **allocated for purchasing quality CNC equipment**
2. CNC **equipment must be maintained** on a regular basis. This can be accomplished by obtaining a full-service contract or by hiring an in-house technician
3. **Personnel** must be thoroughly **trained** in the setup and operation of CNC machines
4. Careful **production planning** must be studied. This is because the hourly cost of operating a CNC machine is usually higher than that for conventional machines

Financial Rewards of CNC Investment

Investors are encouraged to look to the CNC machine tool as a production solution with the following savings benefits:

1. Savings in **direct labor**
2. One CNC machine's output is **commonly equivalent** to several conventional machines
3. **Savings** in **operator training** expenses
4. **Savings** in **shop supervisory** costs
5. **Savings** due to tighter, more **predictable production scheduling**
6. **Savings** in real estate since fewer CNC machines are needed
7. **Savings** in **power consumption** since CNC machines produce parts with a minimum of motor idle time
8. **Savings** from **improved cost estimation** and **pricing**

(Introduction to Computer Numerical Control, 4th EditionJ.V. Valentino, E.V. Goldenberg,2007)

Financial Rewards of CNC Investment

9. **Savings** due to the **elimination of construction of precision jigs**, and the **reduced need for special fixtures**.

   - Maintenance and storage costs of these items are also reduced

10. **Savings** in **tool engineering/design and documentation**

    - The CNC's machining capability eliminates the need for special form tools, special boring bars, special thread cutters, etc.

11. **Reduced inspection time** due to the CNC machine's **ability to produce parts with superior accuracy and repeatability**

    - In many cases, only spot checking of critical areas is necessary without loss of machine time

Financial Rewards of CNC Investment

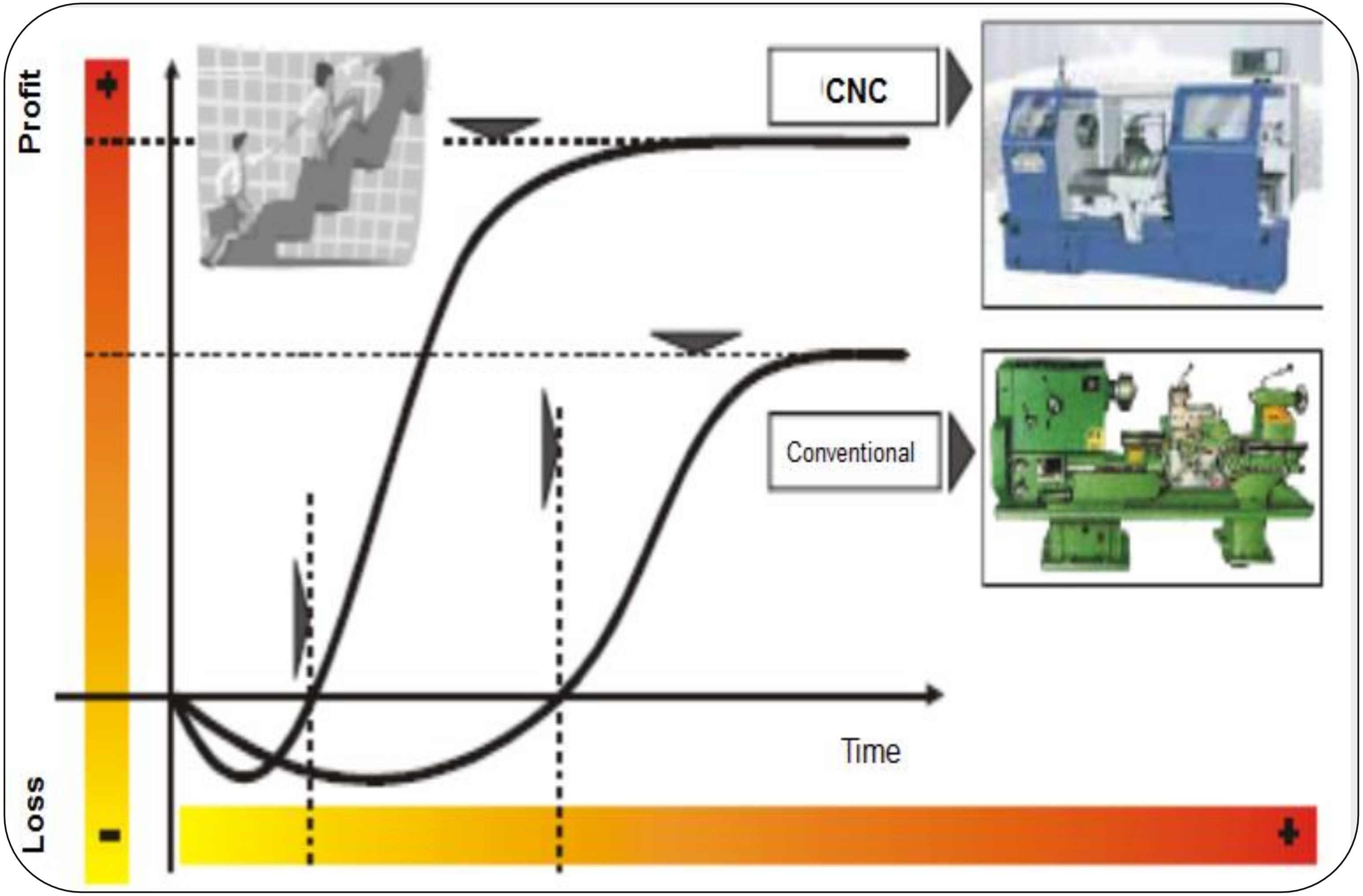


Figure 1-12: Financial Rewards Of CNC Investment

Financial Rewards of CNC Investment

Using Payback Period to Estimate Investment Efficiency

The **Payback Period calculation estimates the number of years required to recover the net cost of the CNC machine tool**

$$\text{Payback Period} = \frac{\text{Net cost of CNC - Net cost of CNC x Tax Credit}}{\text{Savings – Savings x Tax Rate + Yearly Depreciation of CNC x Tax Rate}}$$

Using ROI to Estimate Investment Efficiency

The **ROI calculation** predicts what **percent of the net cost of the CNC will be recovered each year**. The **ROI calculation** accounts for the useful life of the CNC machine tool

$$\text{ROI} = \frac{\text{Average Yearly Savings – Net cost of CNC/ Years of life}}{\text{Net cost of CNC}}$$

Example 1 -1

- Given the investment figures in Table 1-1 for implementing a new CNC machine tool, **determine the payback period** and the **annual return** on investment. The CNC is conservatively estimated to have a useful life of 12 years

Table 1-1

Initial Investment ($)	One-time savings in tooling ($)	Net Cost of CNC ($)	Average yearly savings ($)	Tax Credit (10%)	Tax Rate (46%)	Yearly depreciation of CNC ($)
130,250	35,000	95,250	63,100	0,1	0,46	10,900

$$\text{Payback Period} = \frac{95{,}250 - 95{,}250 \times 0.1}{63{,}100 - 63{,}100 \times 0.46 + 10{,}900 \times 0.46}$$

Payback Period = 2.19 years

- This calculation estimates that the net cost of the CNC will be recovered in 2.19 years

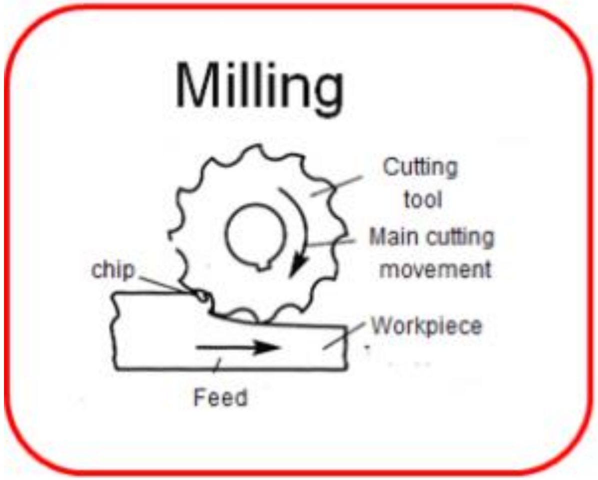
$$\text{ROI} = \frac{63{,}100 - 95{,}250 / 12}{95{,}250}$$

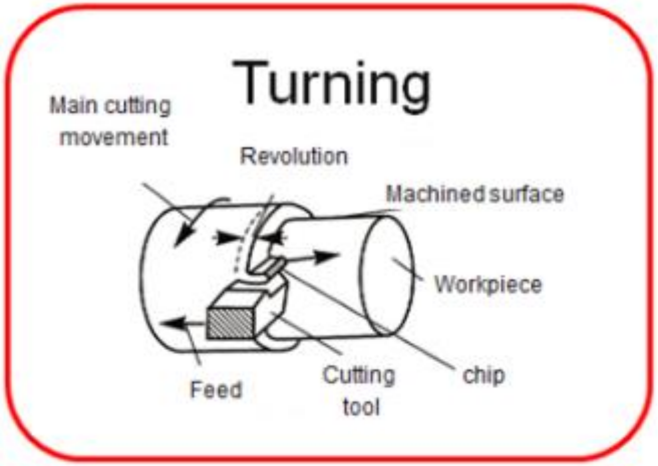
ROI = .57

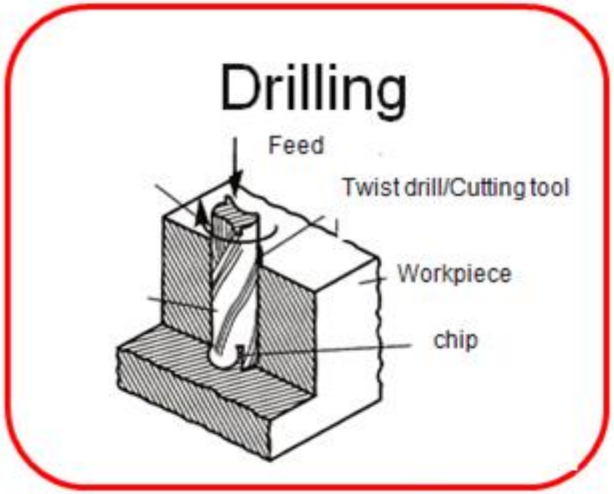
- This calculation estimates that the investor can expect **57%** of the net cost of the CNC or **(.57 x $95,250) = $54,293** to be recovered each year if the CNC machine's useful life is 12 years

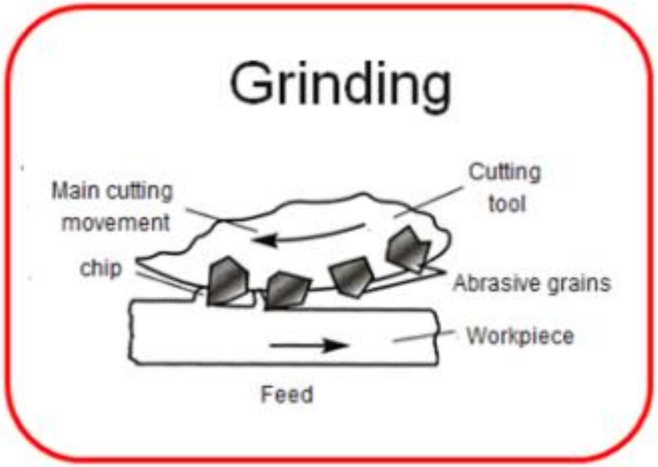
Machining Processes

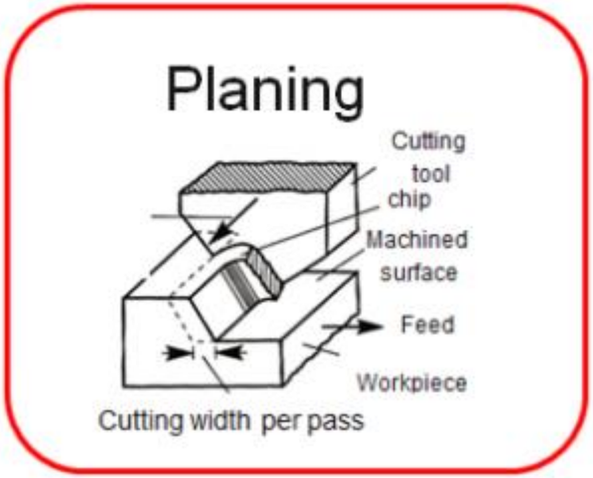
Common Material Removal Processes





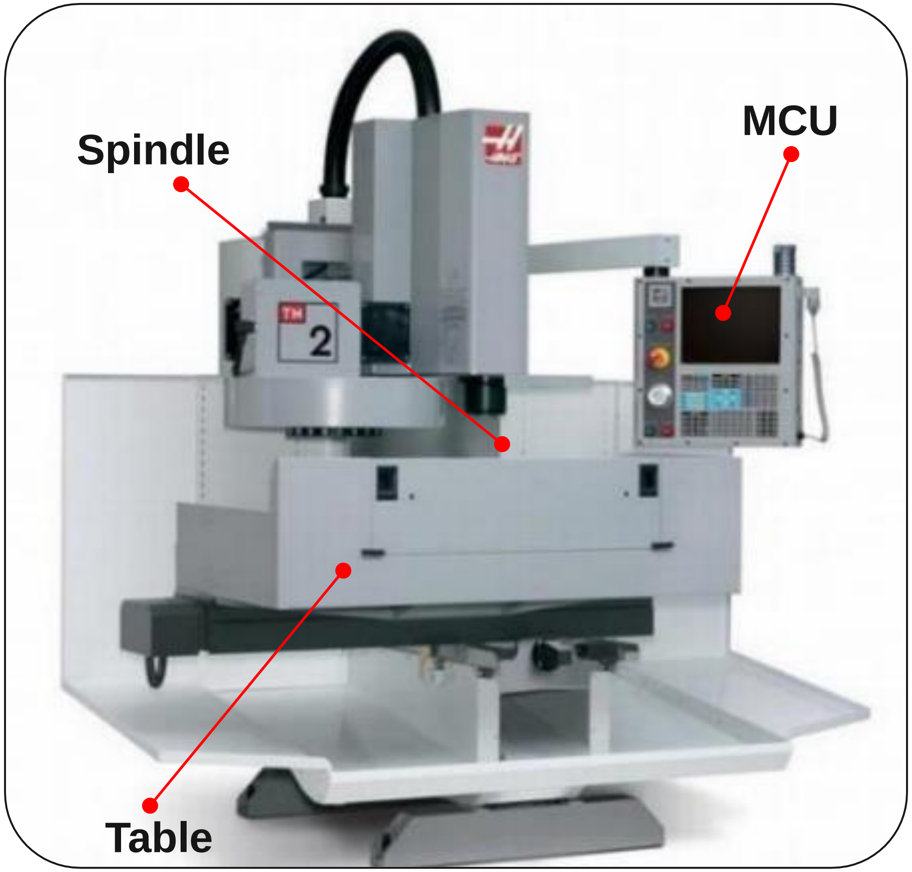






(Adapted by Chryssolouris G., «Manufacturing Systems: Theory and Practice», 2nd Edition, 2006, Springer-Verlag)

CNC Milling Machine



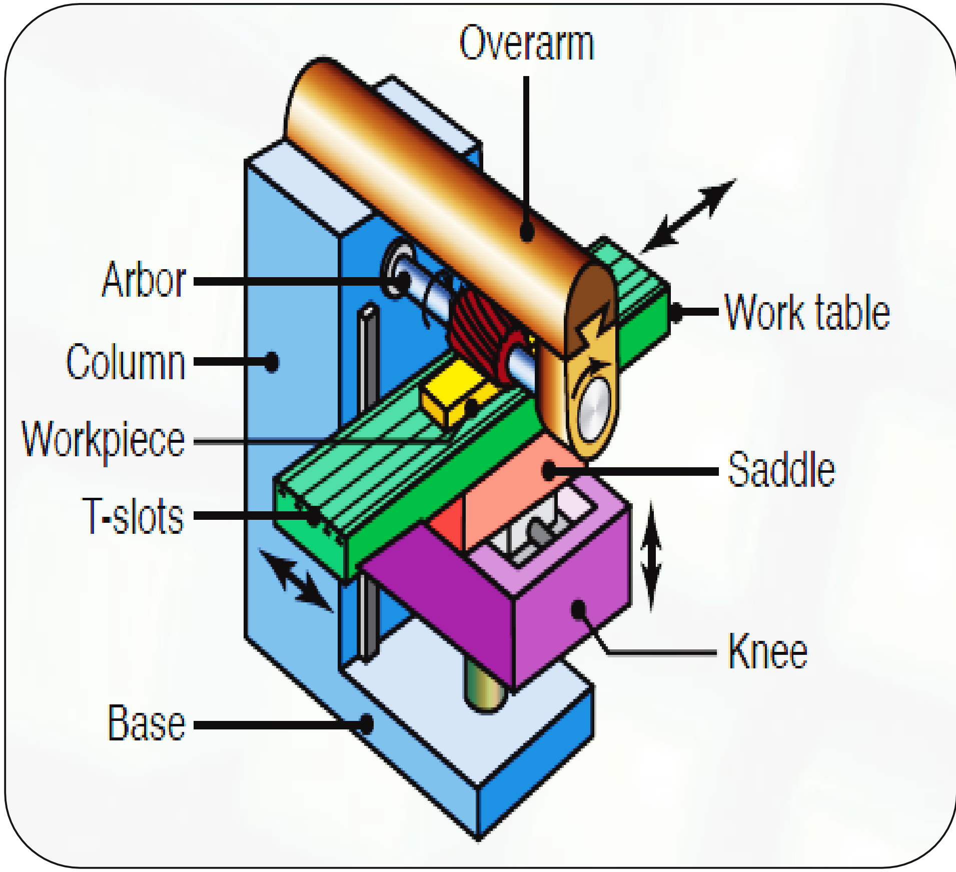


Figure1-3(a): CNC Milling machine

(Source: haascnc.com)

Figure1-14: Schematic illustration of a horizontal-spindle column-and-knee-type milling machine

(Source: Manufacturing Processes for Engineering Materials, 5th ed.Kalpakjian• Schmid 2008)

Machine Components

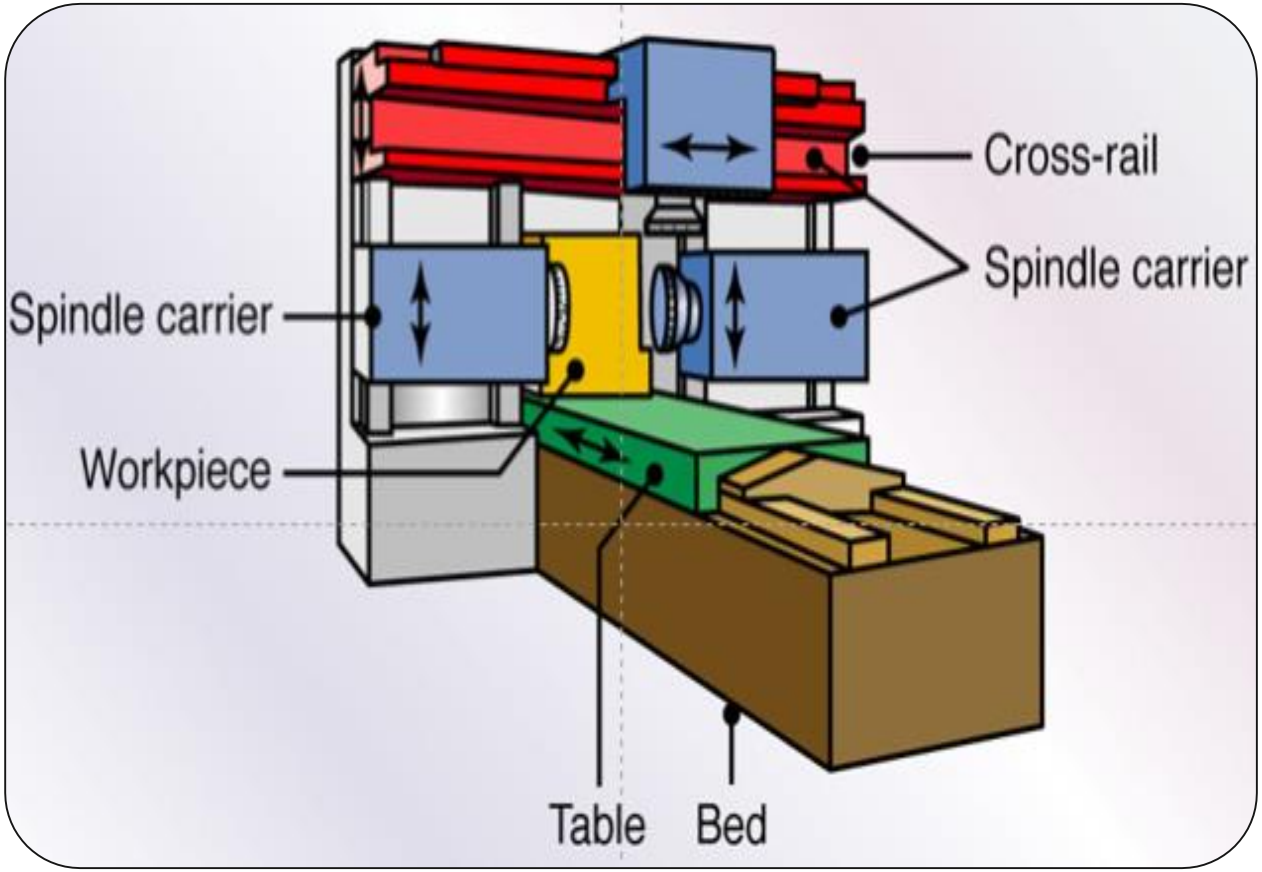


Figure 1-15: A (CNC) vertical-spindle milling machine

(Source :Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid.)

CNC Lathe

Figure 1-16: Haas TL-15 CNC Lathe

(Source:http://int.haascnc.com)

CNC Lathe Components

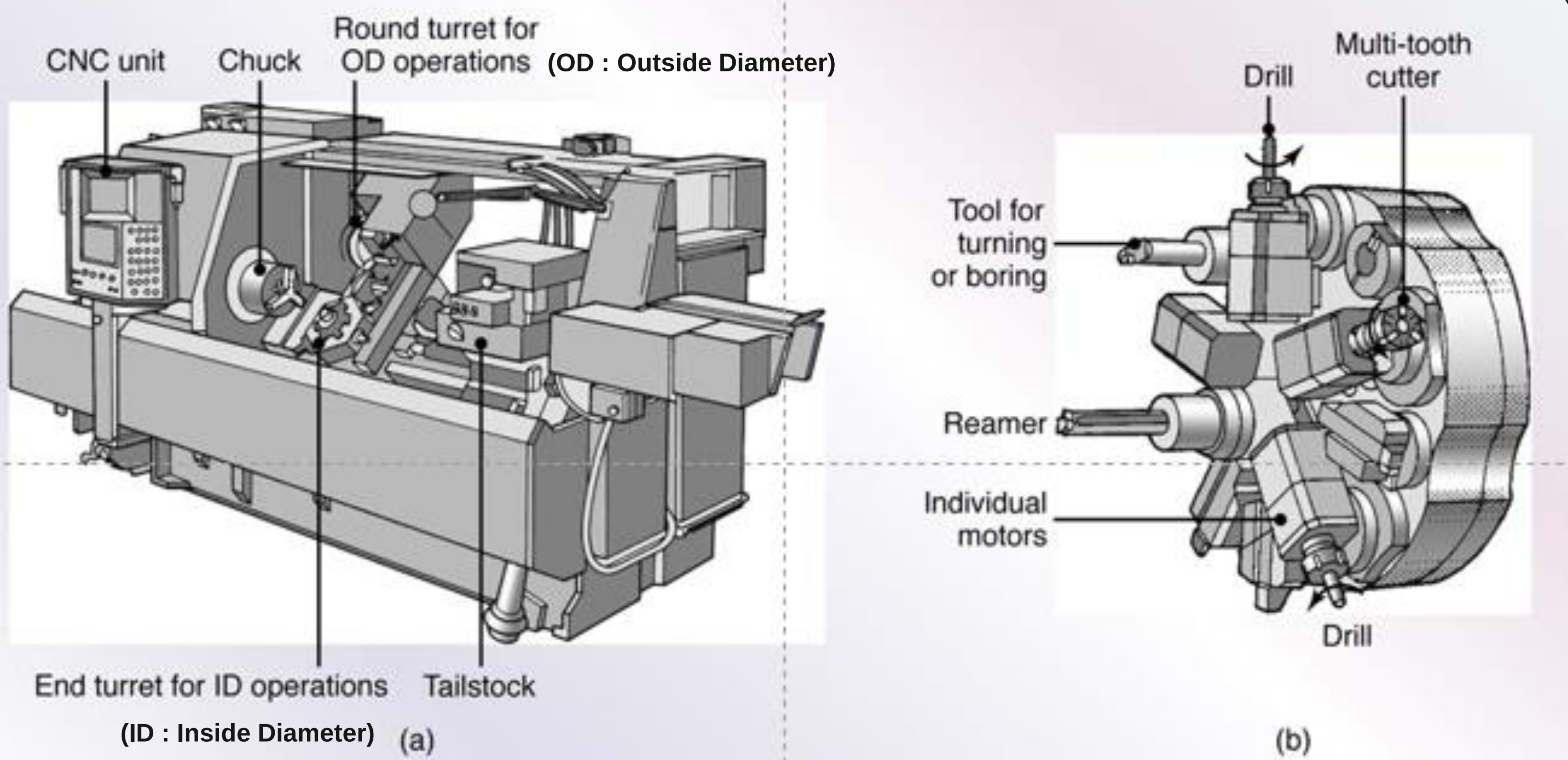


Figure 1-17: A computer numerical-control lathe. These machines have higher power and spindle speed than other lathes in order to take advantage of new cutting tools with enhanced properties. (b) A typical turret equipped with ten tools, some of which are powered. *(Source:Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid.)*

Grinding

Grinding Machine

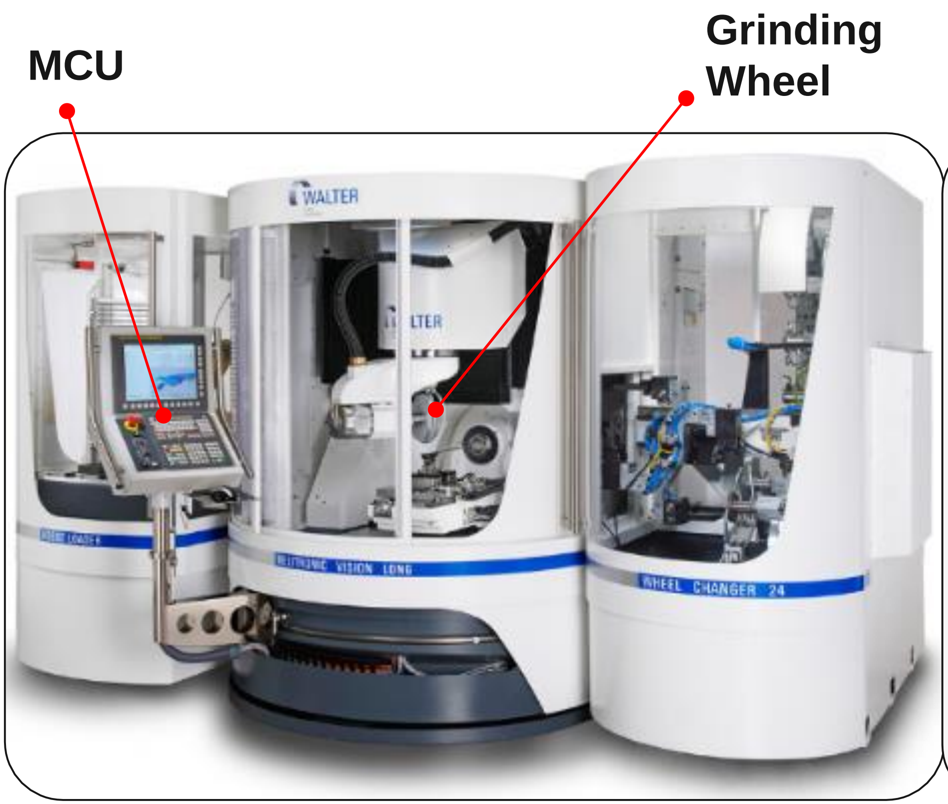


Figure 1-18: Helitronic Vision 5 axis CNC grinding machine*(Source: Walter Maschinenbau)*

Grinding Machine Components

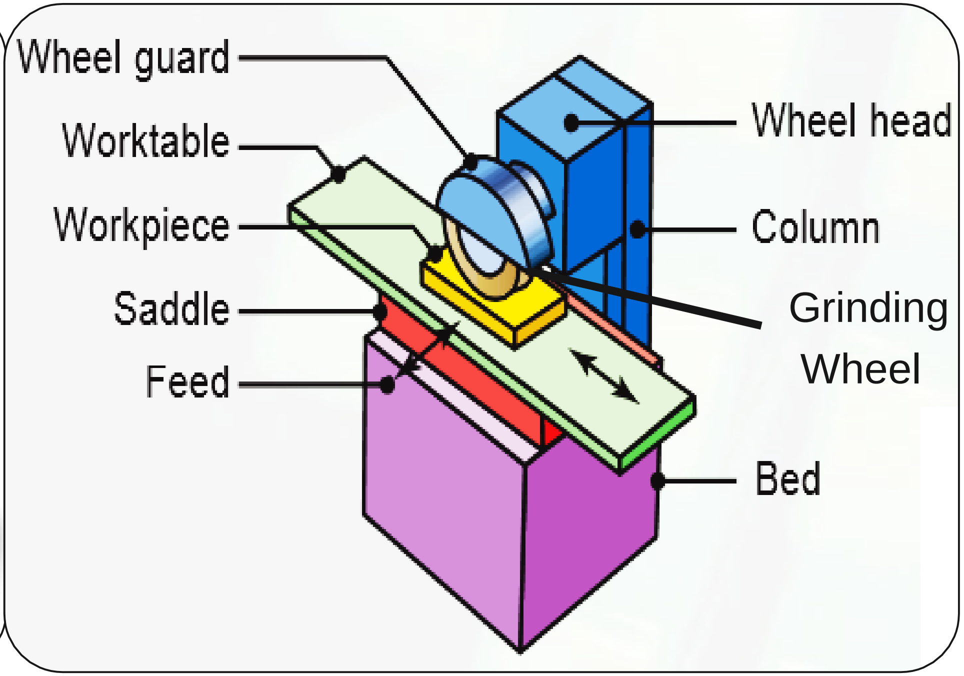
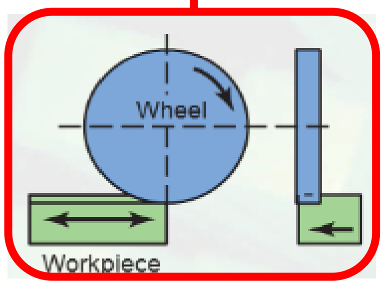


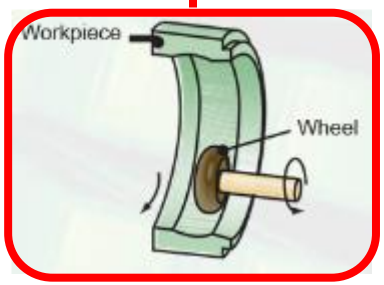
Figure 1-19: Horizontal Surface Grinder
(Adapted by Manufacturing Processes for Engineering Materials, 5th ed.Kalpakjian• Schmid 2008)

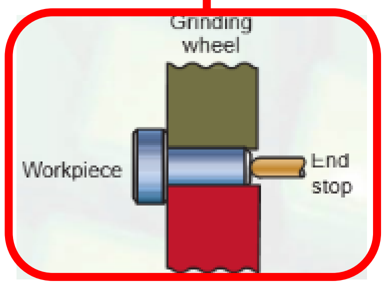
Grinding Methods

Grinding Methods

- Surface Grinding
- Internal Grinding
- External Grinding
- Creep-Feed Grinding







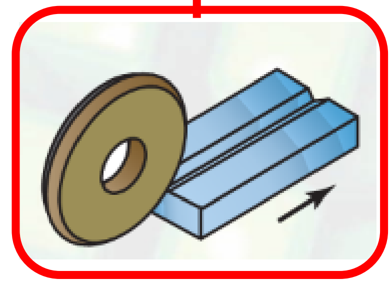


Figure 1-20:Grinding Processes

(Source: Manufacturing Processes for Engineering Materials, 5th ed.Kalpakjian• Schmid 2008)

Centerless Grinding

- When both **high precision** and **quality** are required and grinding must be used, whilst a high production rate is also required, as in the automotive industry, it is **Centerless grinding** that provides a solution

(Chryssolouris G., «Manufacturing Systems: Theory and Practice», 2nd Edition, 2006, Springer-Verlag)

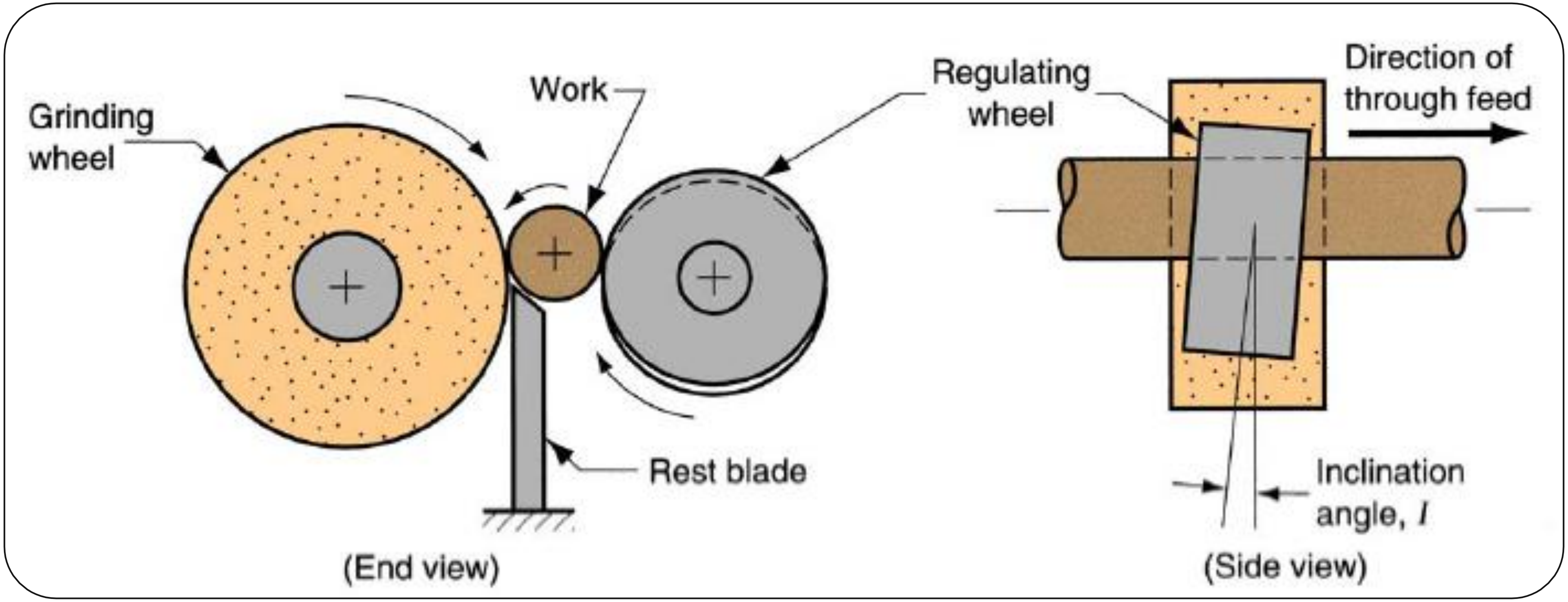
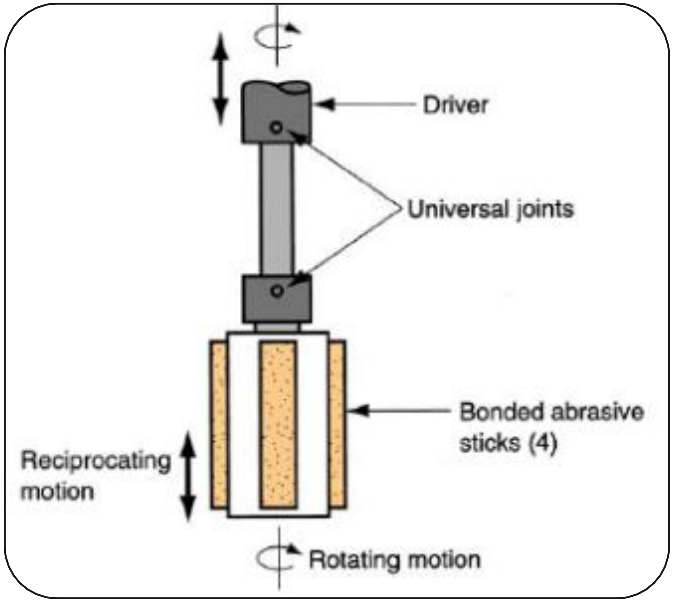


Figure 1-21: Centerless Grinding

Honing

- For **internal cylindrical surfaces** grinding
- **Abrasive sticks** arranged circumferentially are pressed by springs from the inside out

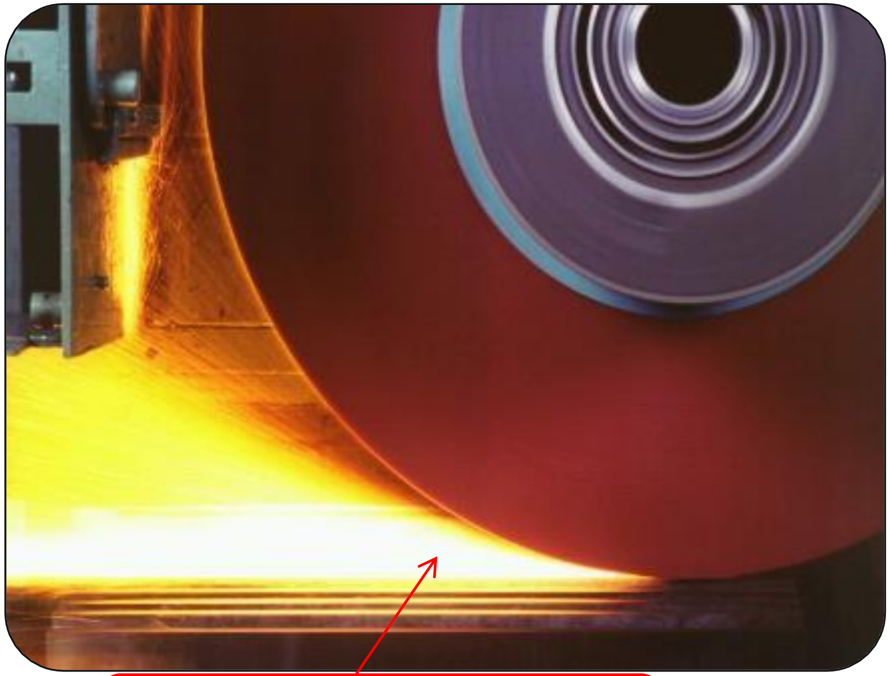


- Concentrates on **surface finish** and **dimensional accuracy**

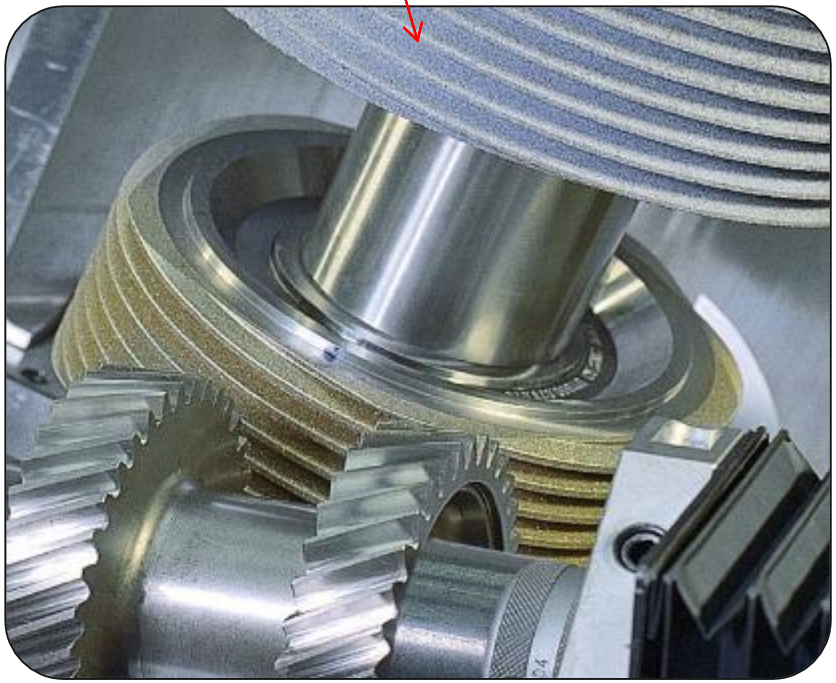
(Chryssolouris G., «Manufacturing Systems: Theory and Practice», 2nd Edition, 2006, Springer-Verlag)

Grinding

Other types of Grinding



Grind Hardening



Profile Grinding

(CIRP Annals - Manufacturing Technology Volume 48, Issue 1, 1999, Pages 255–260 Grind-Hardening: A Comprehensive View ,T. Brockhoffa, E. Brinksmeierb)

(Chryssolouris G., «Manufacturing Systems: Theory and Practice», 2nd Edition, 2006, Springer-Verlag)

CNC Drilling Machine

Figure1-22:A computer numerical-control drilling machine *(Source: http://www.emi-mec.eu/)*

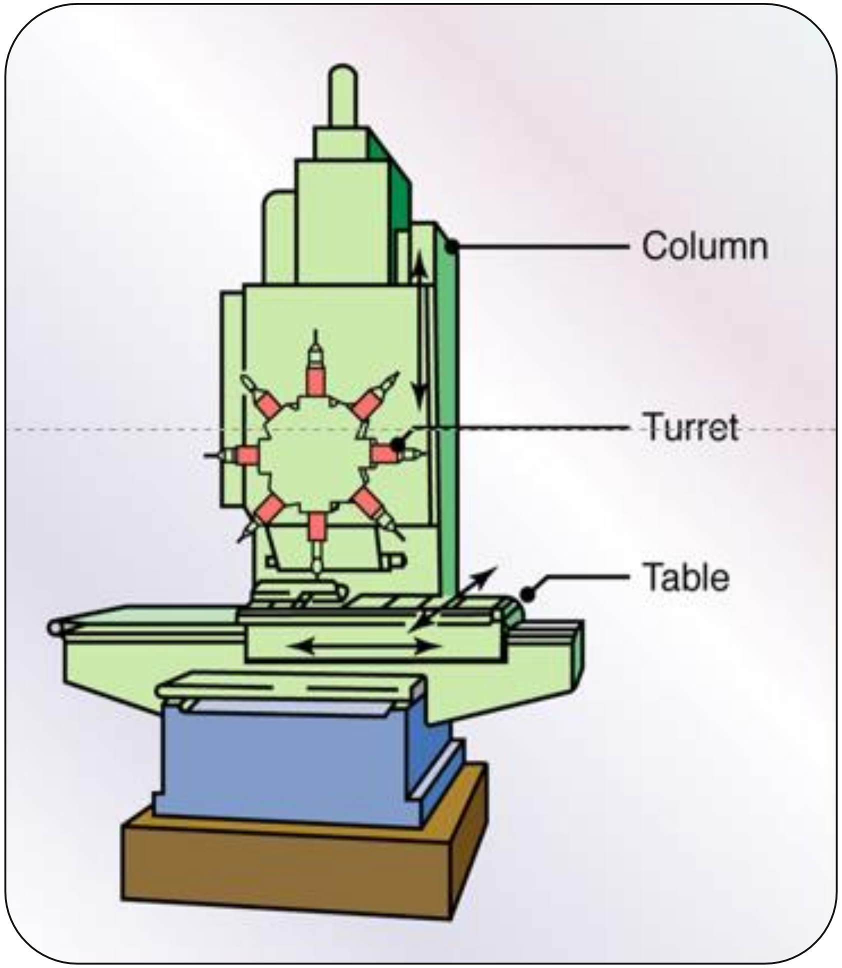


Figure1-23 : A three-axis CNC drilling machine

(Source: Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid)

Planing

Machine Components

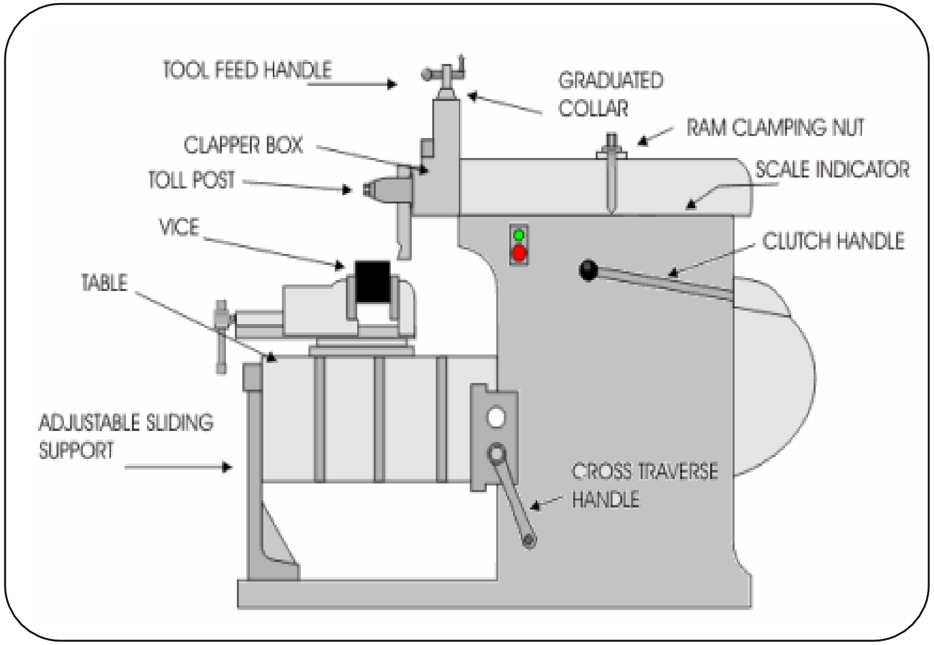


Figure 1-24: Planer main parts

(Photo courtesy of V. Ryan 2003)

Parts made on a Planer

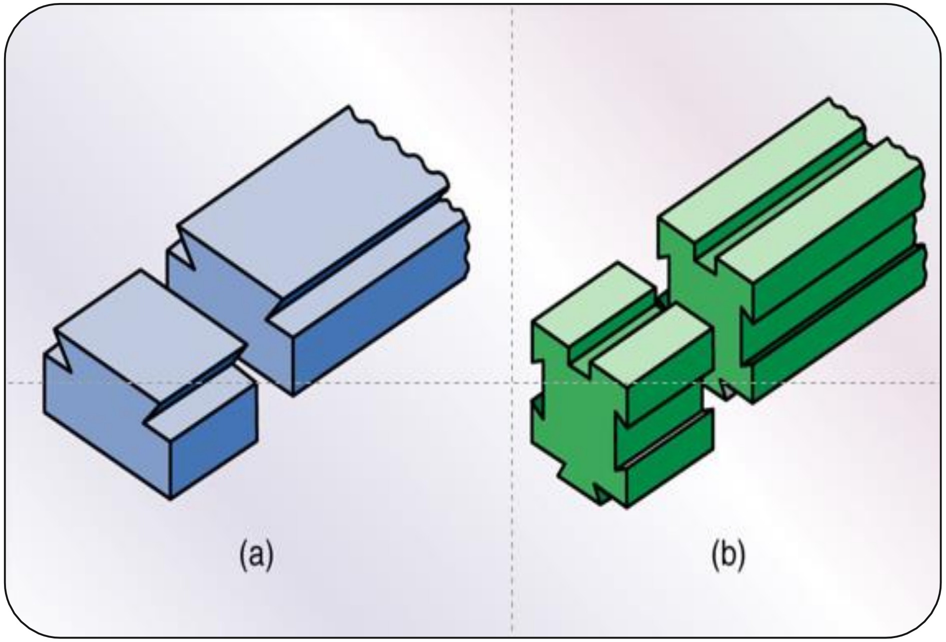


Figure 1-25: Typical parts that can be made on a planer

(Source :Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid.)

Summary 1/3

- Some **good reasons to automate** are: **Improvement of quality** and customer satisfaction, **faster responding to market changes** and business **expansion to new markets**
- An **NC** machine is a machine positioned **automatically** along a **preprogrammed** path by way of coded instructions
- **DNC** involves a computer that acts as a **partial or full controller** to one or more NC machines
- **Distributive NC** is a network of computers and NC machinery coordinated to perform some task
- **CNC machines** use an on-board computer as a controller

Summary 2/3

- **Offline programming** is the programming of a part away from the computer keyboard - usually done with a micro-computer

- There are four ways to input programs into CNC machinery:
  - **MDI** (Manual Data Input)
  - **Punched** Tape
  - **Magnetic** Tape
  - **DNC** (Direct Numerical Control / Distributive Numerical Control)

- The **CNC** program must be loaded into the controller in **binary** form

- **RS-244** and **RS-358** tape codes used to place information on punched tape information being punched into the tape in binary form

Summary 3/3

- Before deciding on a NC machine for a specific job, the **advantages and disadvantages of NC must be weighed** in view of the primary objectives of numerical control

- Five material removal processes are also mentioned: **Planing, Milling, Turning, Drilling** and **Grinding**

- Main objectives of **cooling** during milling are :**heat removal** in the cutting area and **friction reduction** between material and cutter

- The general rule when selecting grinding wheel is that: **Soft wheels for hard materials and hard wheels for soft materials**

Vocabulary Introduced in this chapter

- ASCII
- Binary coded decimal (BCD)
- Computer Aided Programming (CAP)
- Computer Numerical Control (CNC)
- Direct Numerical Control (DNC)
- Distributive numerical control
- Input media
- Manual Data Input (MDI)
- Manual part programming
- Numerical control (NC)
- Random Access Memory (RAM)
- Read-only Memory (ROM)
- Word address format

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