MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1861

2.810 Manufacturing Processes and Systems

Prof. Tim Gutowski, gutowski@mit.edu

September 4, 2019

Prereq: 2.001, 2.006, 2.008

(translation: solid & fluid mech, heat transfer, mfg)

Today’s Agenda

- Business
  - Administrative stuff
  - Your background
- Concepts
  - Manufacturing Enterprise – Big Picture
  - Processes
  - Systems

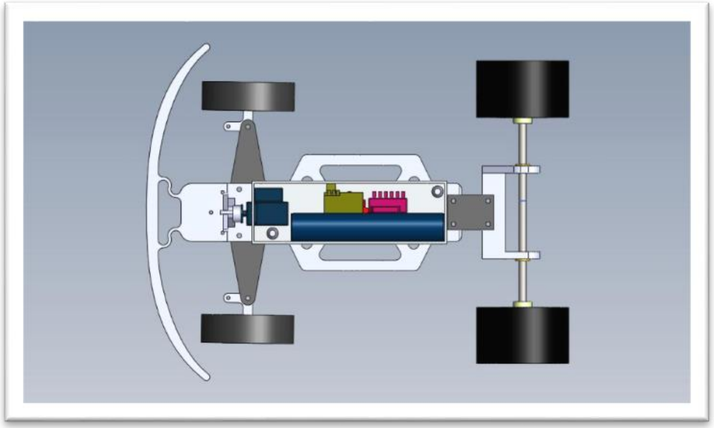
Basic info can be found on the 2.810 webpage

web page:	*http://web.mit.edu/2.810/www*	
Instructor:	*Prof. T. G. Gutowski* *gutowski@mit.edu*	*Rm. 35-234*
T.A.:	*John Lewandowski* *dowski@MIT.EDU*	*Rm 35- 135*
Tech Inst:	*Mr. Paul Carson* *pcarson@mit.edu*	*Rm. 35-112*
Text:	***Manufacturing Engineering and Technology, 7th Ed.*** *Kalpakjian and Schmid, 2014. Prentice Hall.*	

Paul Carson & the Bldg 35 Shop

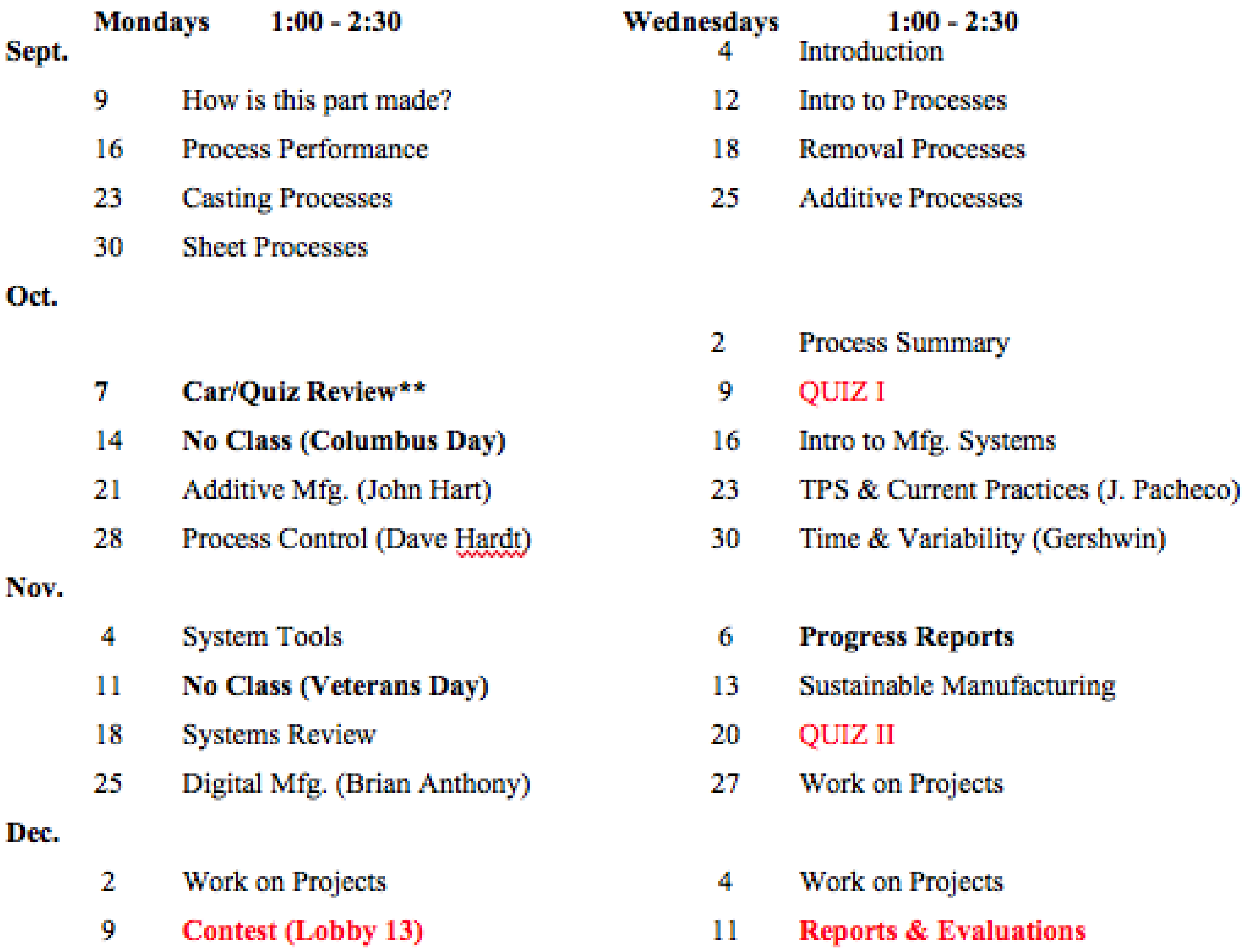
pcarson@mit.edu

Hands-on Experience



Processes to Systems

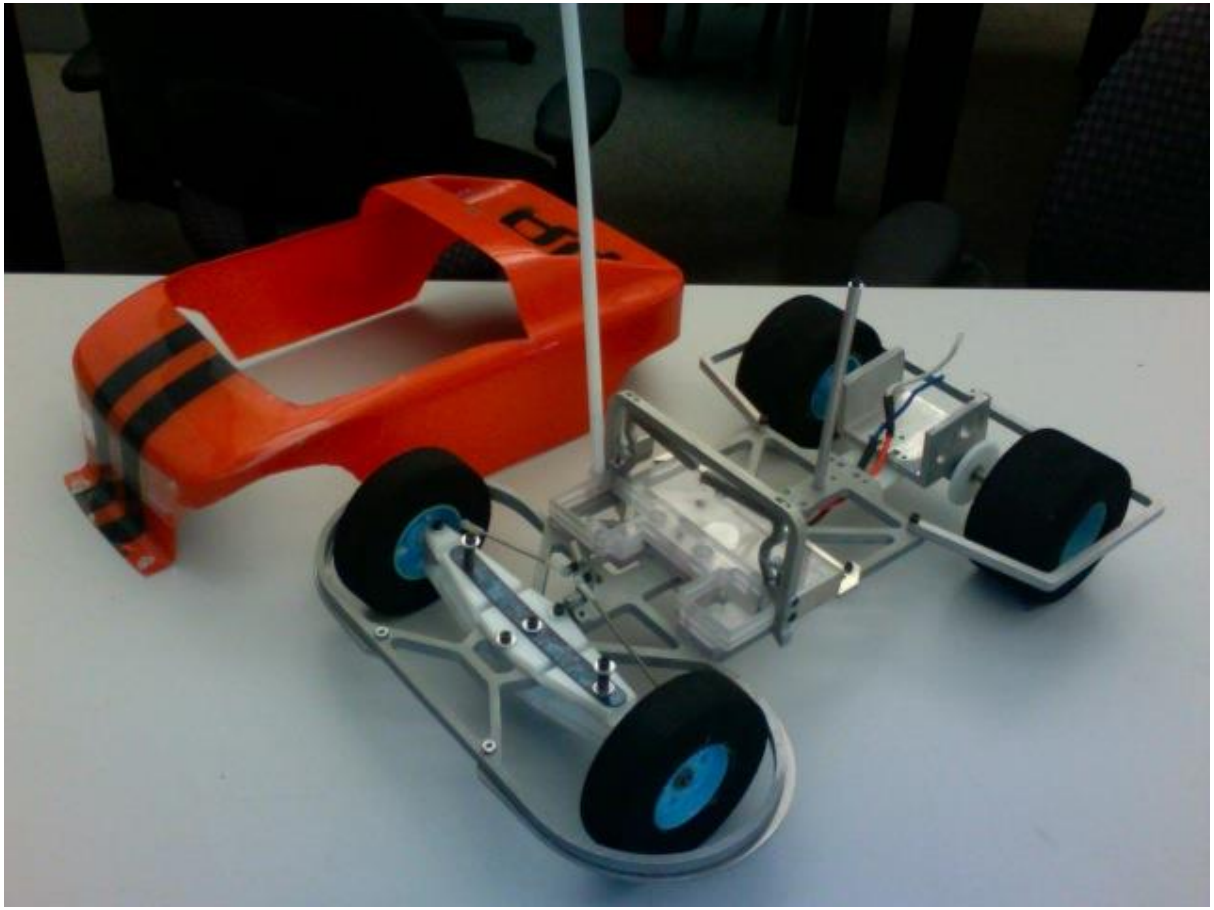
2.810 Schedule



	Mondays	**1:00 - 2:30**	**Wednesdays**	**1:00 - 2:30**
Sept.			4	Introduction
	9	How is this part made?	12	Intro to Processes
	16	Process Performance	18	Removal Processes
	23	Casting Processes	25	Additive Processes
	30	Sheet Processes		
Oct.				
			2	Process Summary
	7	**Car/Quiz Review****	9	QUIZ I
	14	**No Class (Columbus Day)**	16	Intro to Mfg. Systems
	21	Additive Mfg. (John Hart)	23	TPS & Current Practices (J. Pacheco)
	28	Process Control (Dave Hardt)	30	Time & Variability (Gershwin)
Nov.				
	4	System Tools	6	**Progress Reports**
	11	**No Class (Veterans Day)**	13	Sustainable Manufacturing
	18	Systems Review	20	QUIZ II
	25	Digital Mfg. (Brian Anthony)	27	Work on Projects
Dec.				
	2	Work on Projects	4	Work on Projects
	9	**Contest (Lobby 13)**	11	**Reports & Evaluations**

* https://www.youtube.com/watch?v=ICjQ0UzE2Ao

2.810 team project



2.810 Labs (see signup)

Labs 9-12 M, T, R, F; Building 35 shop

Week of September 9	Safety, Shop Orientation, Car Review
Week of September 16	**Machining /Flashlight Project**
Week of September 23	**Machining /Flashlight Project**
Week of September 30	**Machining /Flashlight Project**
Week of October 7	CAD/CAM (by appointment with Paul)
Week of October 16	Finish up Lab
Week of October 21	Car Project (this continues through term)

Lab Maximum 16 people

Teams and Labs are Different

- Labs occur at the beginning of the term:

  basic skills some CNC

- Teams are to build cars: you select your team members, usually 4 to 6 per team

Key dates for project

Sept 16 - Teams finalized

Sept 30 - Kits assembled

Week of Sept 30 - Preliminary design concept review
(schedule a time for group to meet with Paul)

Week of Oct 14 - Injection mold wheels

October 21 - Chassis drawings due
(waterjet file and dimensioned drawing)

Week of Oct 28 - Production chassis cut on waterjet

November 6 - Oral Progress Reports

December 9 - Contest

December11 - Evaluation & Reports

Available at 2.810 Website

Please fill out information form; background, interests, skills

- Basic information
- Experience in shop
- Experience in mfg

2.810 Manufacturing Processes and Systems

Name: ____

Year: ____________________ **Course:** ____________________

Email: ___________________

Prerequisites (Please check off it taken):

2.001 or equivalent ☐

2.006 ☐

2.008 ☐

Previous experience in industry/research/manufacturing, please describe

____

____

____

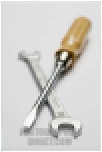
____

If you have had significant manufacturing experience, would you be interested in giving a short "show & tell" (about 5-10 min) to the class if we can schedule it?

______ **Y** ______ **N**

List the Topic: ____

2.810 Hands-on Experience Questionnaire

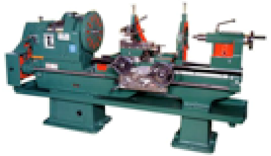


Are you familiar with these tools? Can you use them? ☐ ☐
Y N

Are you comfortable using power tools? ☐ ☐
Y N

Have you ever built or repaired something? ☐ ☐
Ex: Built a boat, repaired a lawn mower etc. Y N
What specifically did you do? ____________________

____



Have you ever used - an engine lathe? ☐ ☐
- band saw? ☐ ☐
- drill press? ☐ ☐
Y N

Are you comfortable in a machine shop and can operate machine tools without supervision? ☐ ☐
Y N

Can you program CNC machine tools? ☐ ☐
Y N

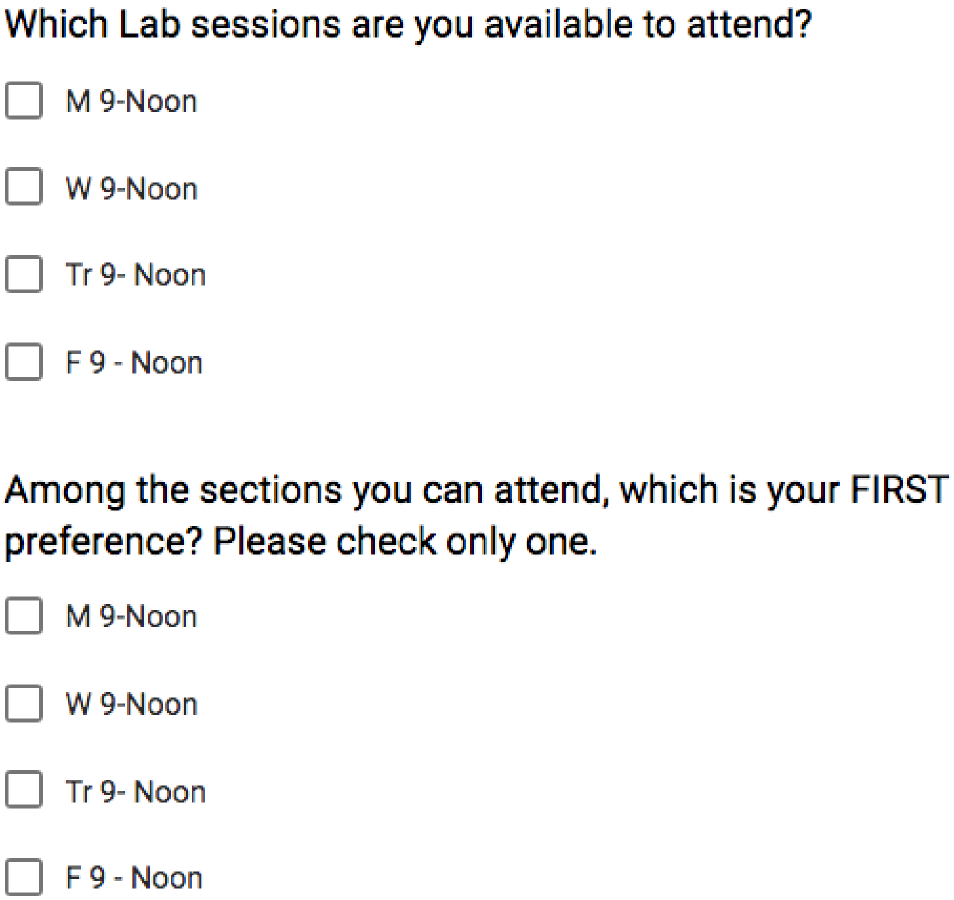
Please list any CAD/CAM software you already have experience with:

1. **2.** **3.**

Lab Sign-up

- See Google Doc: web & email
- State your availability & preference
- See schedule (don’t miss first 5 weeks)

Labs & Copies (9 per sheet Y_ or N_?)



Which Lab sessions are you available to attend?

☐ M 9-Noon

☐ W 9-Noon

☐ Tr 9- Noon

☐ F 9 - Noon

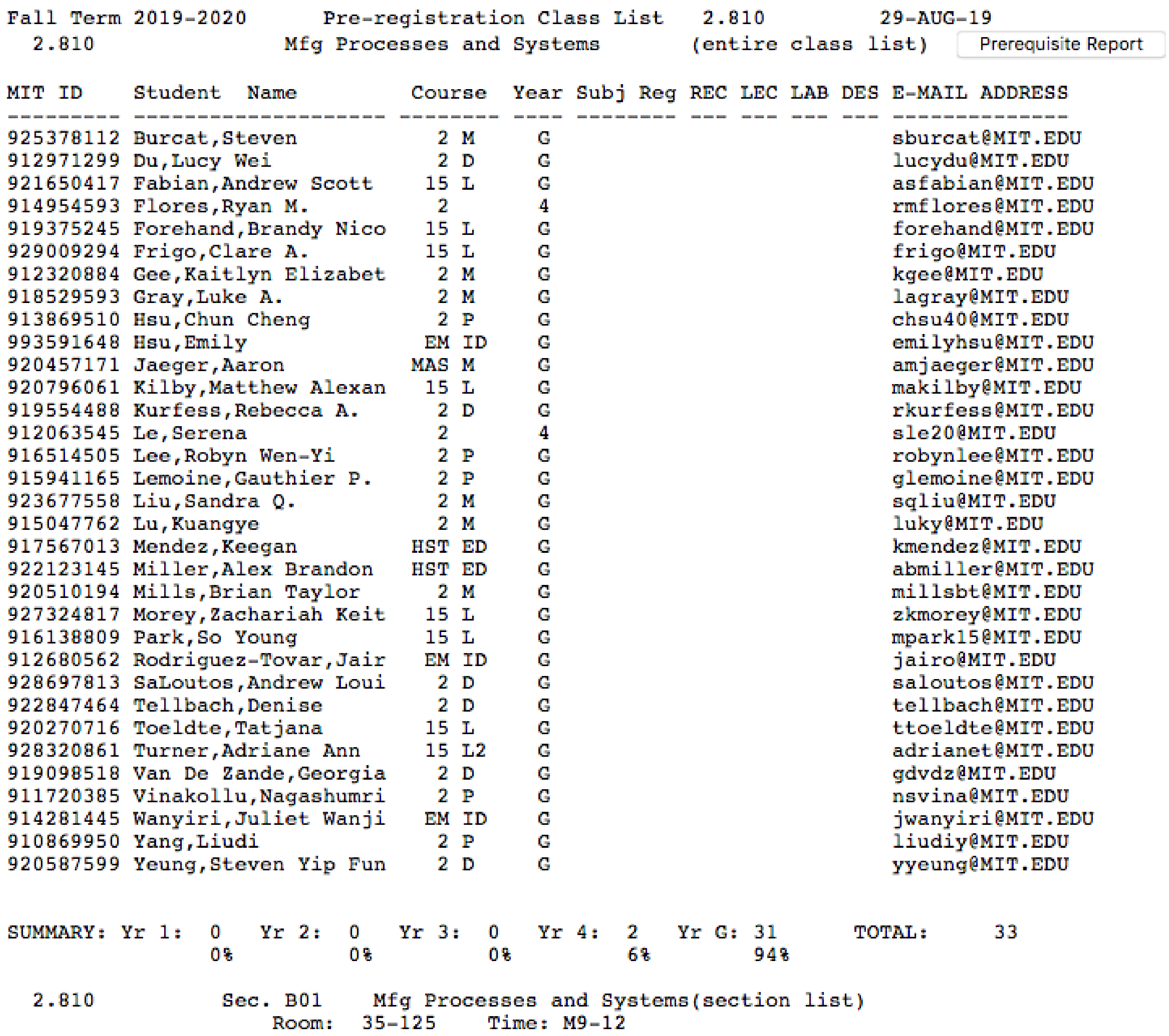
Among the sections you can attend, which is your FIRST preference? Please check only one.

☐ M 9-Noon

☐ W 9-Noon

☐ Tr 9- Noon

☐ F 9 - Noon



```
Fall Term 2019-2020      Pre-registration Class List    2.810         29-AUG-19
  2.810                Mfg Processes and Systems       (entire class list)

MIT ID     Student  Name          Course  Year Subj Reg REC LEC LAB DES E-MAIL ADDRESS
---------- -------------------- -------- ---- -------- --- --- --- --- ---------------
925378112 Burcat,Steven           2 M      G                           sburcat@MIT.EDU
912971299 Du,Lucy Wei             2 D      G                           lucydu@MIT.EDU
921650417 Fabian,Andrew Scott    15 L      G                           asfabian@MIT.EDU
914954593 Flores,Ryan M.          2        4                           rmflores@MIT.EDU
919375245 Forehand,Brandy Nico   15 L      G                           forehand@MIT.EDU
929009294 Frigo,Clare A.         15 L      G                           frigo@MIT.EDU
912320884 Gee,Kaitlyn Elizabet    2 M      G                           kgee@MIT.EDU
918529593 Gray,Luke A.            2 M      G                           lagray@MIT.EDU
913869510 Hsu,Chun Cheng          2 P      G                           chsu40@MIT.EDU
993591648 Hsu,Emily              EM ID     G                           emilyhsu@MIT.EDU
920457171 Jaeger,Aaron          MAS M      G                           amjaeger@MIT.EDU
920796061 Kilby,Matthew Alexan   15 L      G                           makilby@MIT.EDU
919554488 Kurfess,Rebecca A.      2 D      G                           rkurfess@MIT.EDU
912063545 Le,Serena               2        4                           sle20@MIT.EDU
916514505 Lee,Robyn Wen-Yi        2 P      G                           robynlee@MIT.EDU
915941165 Lemoine,Gauthier P.     2 P      G                           glemoine@MIT.EDU
923677558 Liu,Sandra Q.           2 M      G                           sqliu@MIT.EDU
915047762 Lu,Kuangye              2 M      G                           luky@MIT.EDU
917567013 Mendez,Keegan         HST ED     G                           kmendez@MIT.EDU
922123145 Miller,Alex Brandon   HST ED     G                           abmiller@MIT.EDU
920510194 Mills,Brian Taylor      2 M      G                           millsbt@MIT.EDU
927324817 Morey,Zachariah Keit   15 L      G                           zkmorey@MIT.EDU
916138809 Park,So Young          15 L      G                           mpark15@MIT.EDU
912680562 Rodriguez-Tovar,Jair   EM ID     G                           jairo@MIT.EDU
928697813 SaLoutos,Andrew Loui    2 D      G                           saloutos@MIT.EDU
922847464 Tellbach,Denise         2 D      G                           tellbach@MIT.EDU
920270716 Toeldte,Tatjana        15 L      G                           ttoeldte@MIT.EDU
928320861 Turner,Adriane Ann     15 L2     G                           adrianet@MIT.EDU
919098518 Van De Zande,Georgia    2 D      G                           gdvdz@MIT.EDU
911720385 Vinakollu,Nagashumri    2 P      G                           nsvina@MIT.EDU
914281445 Wanyiri,Juliet Wanji   EM ID     G                           jwanyiri@MIT.EDU
910869950 Yang,Liudi              2 P      G                           liudiy@MIT.EDU
920587599 Yeung,Steven Yip Fun    2 D      G                           yyeung@MIT.EDU


SUMMARY: Yr 1:  0    Yr 2:  0    Yr 3:  0    Yr 4:  2    Yr G: 31      TOTAL:     33
                0%          0%          0%          6%         94%

  2.810          Sec. B01    Mfg Processes and Systems(section list)
                     Room:  35-125    Time: M9-12
```

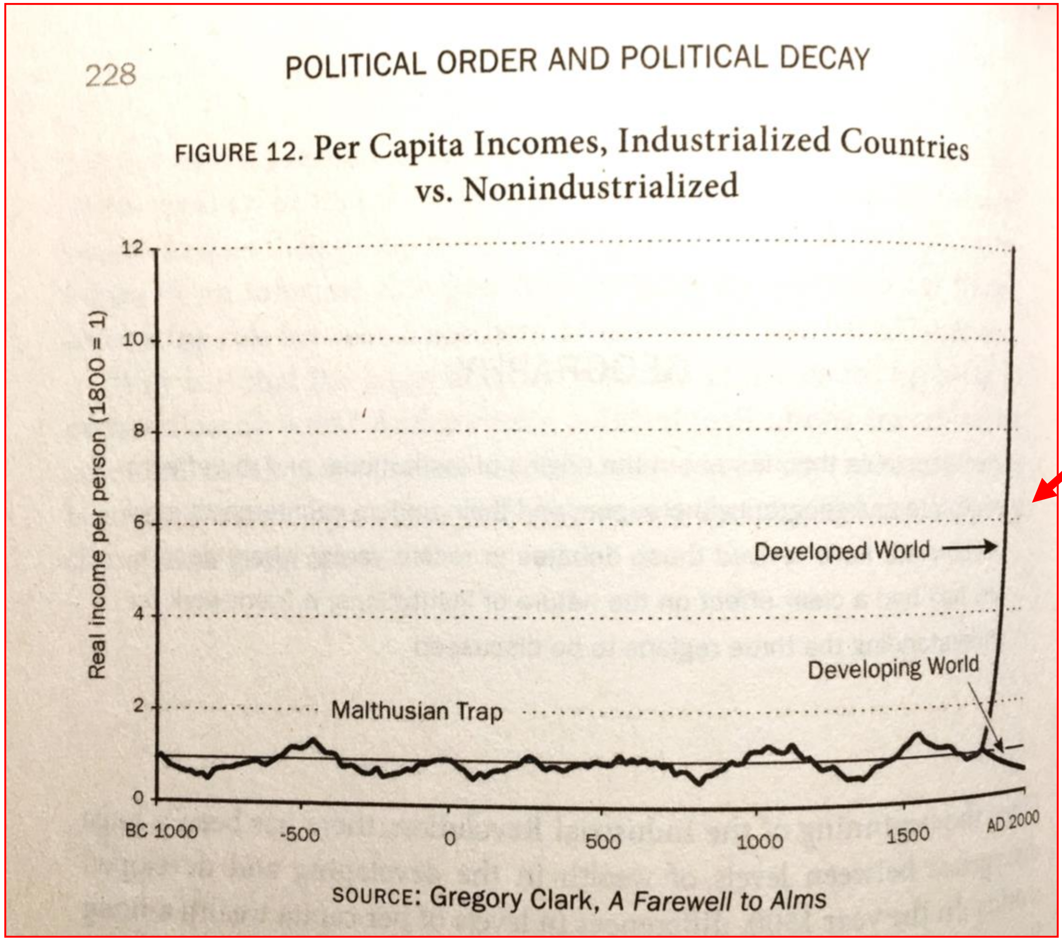
Grading

- Quiz 1 30%
- Quiz 2 30%
- Project 30% (team grade)
- Participation 10%
- Total 100%

The Mfg Enterprise – Big Picture

- Industrialization and Economic Growth
- Big Push Industrialization
- Divergence
- Democracy and Political Development
- The Future: Technology? Growth? Employment? Environment?

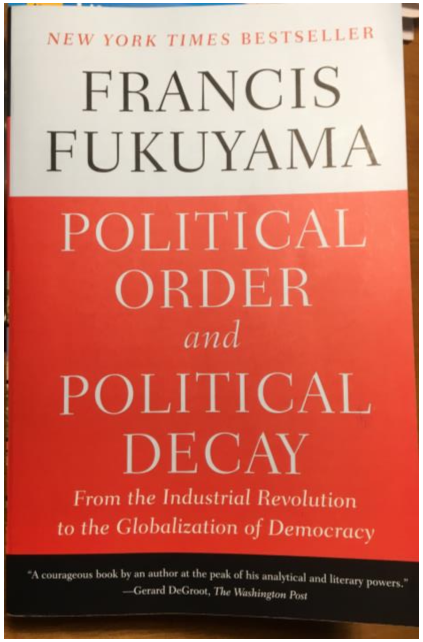
What caused this surge in per capita income around 1800 AD?



228 POLITICAL ORDER AND POLITICAL DECAY

FIGURE 12. Per Capita Incomes, Industrialized Countries vs. Nonindustrialized

SOURCE: Gregory Clark, *A Farewell to Alms*



NEW YORK TIMES BESTSELLER

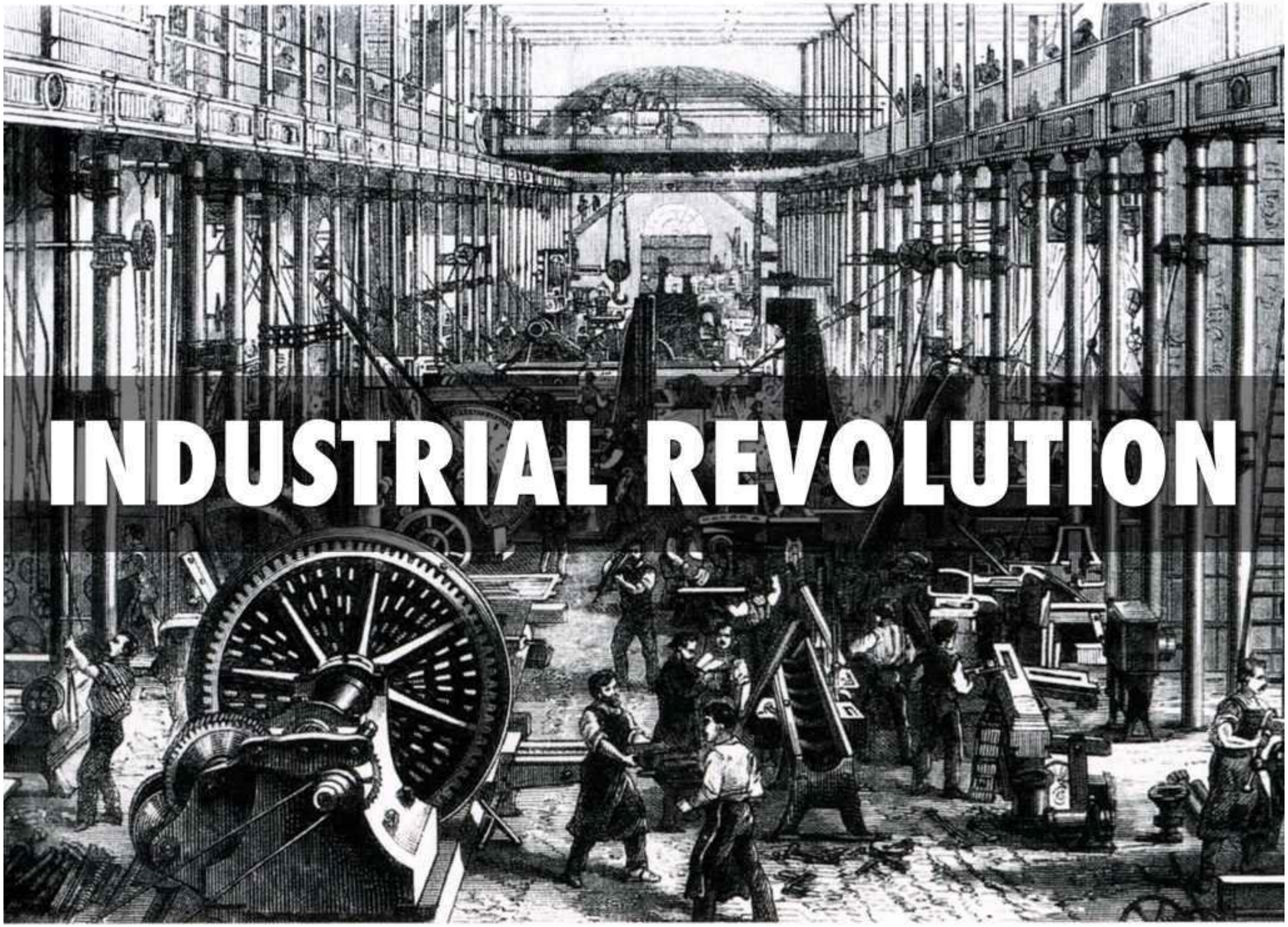
FRANCIS FUKUYAMA

POLITICAL ORDER *and* POLITICAL DECAY

From the Industrial Revolution to the Globalization of Democracy

"A courageous book by an author at the peak of his analytical and literary powers."
—Gerard DeGroot, *The Washington Post*

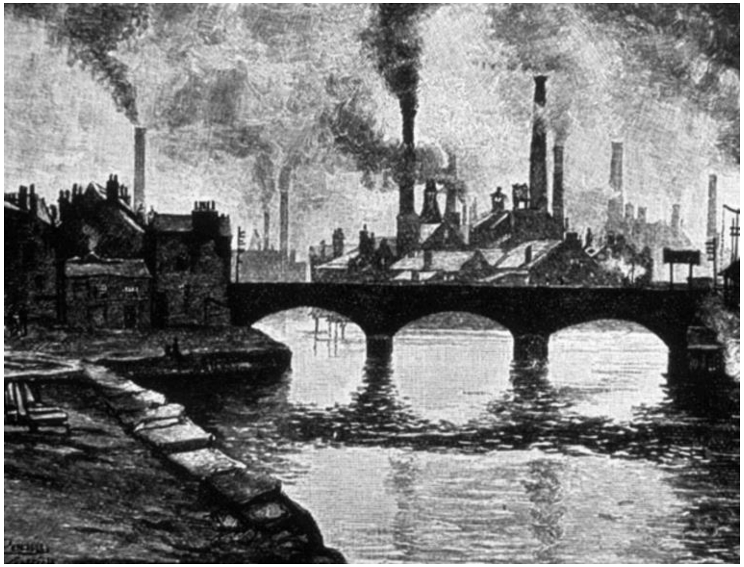
Ref. p 228



http://www.historydiscussion.net/history/industrial-revolution/history-of-the-industrial-revolution/1784

The Industrial Revolution

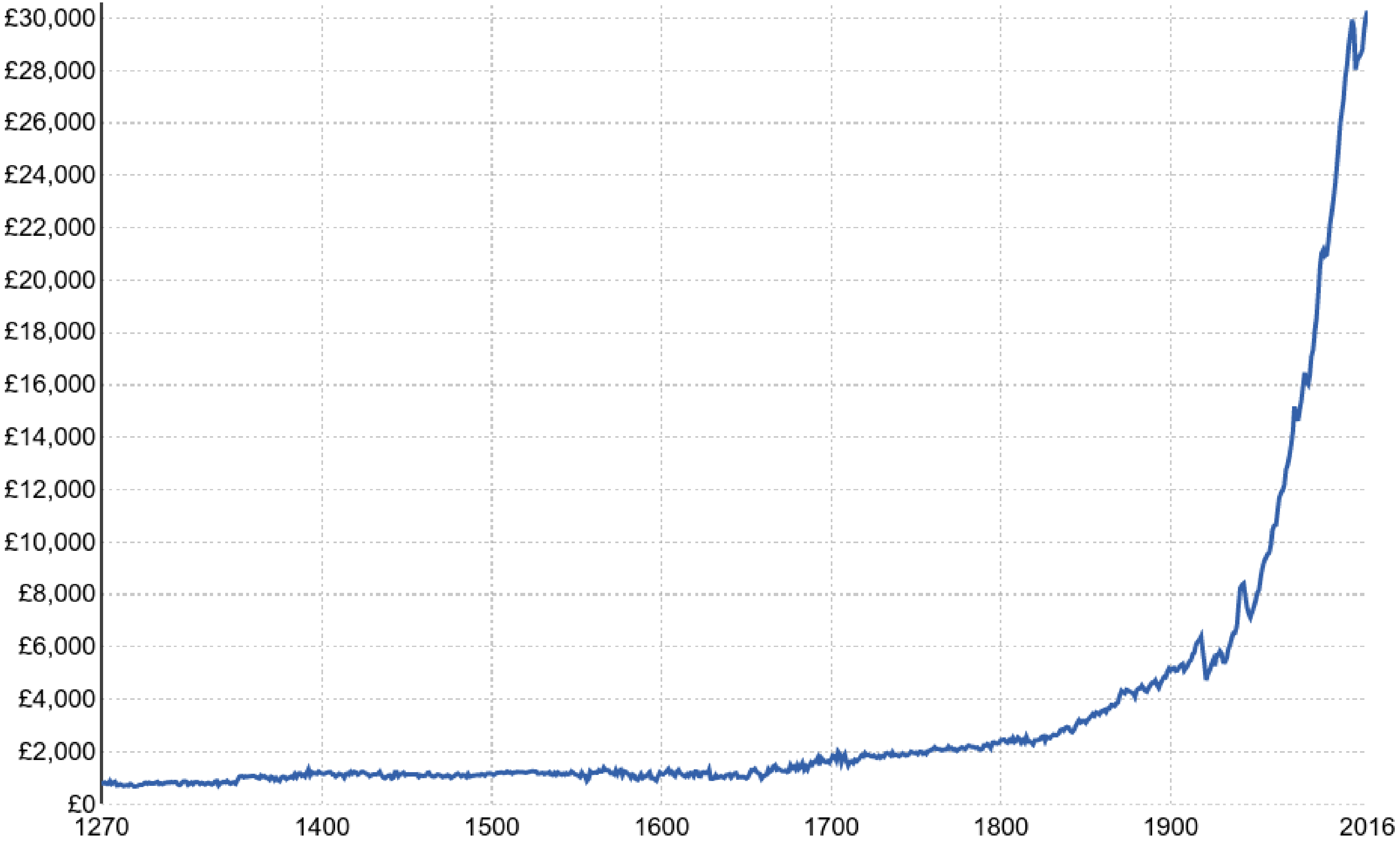
- England 1760 – 1830s
- Coal
- Steam power
- Textile mills
- Steel
- Railroads
- Pollution



https://sites.google.com/a/online.sd71.bc.ca/human-rights-morgan-rachel-rylee/the-industrial-revolution

GDP per capita in England since 1270

Adjusted for inflation and measured in British Pounds in 2013 prices



Source: GDP in England (using BoE, 2017)
Note: Data refers to England until 1700 and the UK from then onwards.

OurWorldInData.org/economic-growth • CC BY-SA

The importance of Manufacturing to economic growth

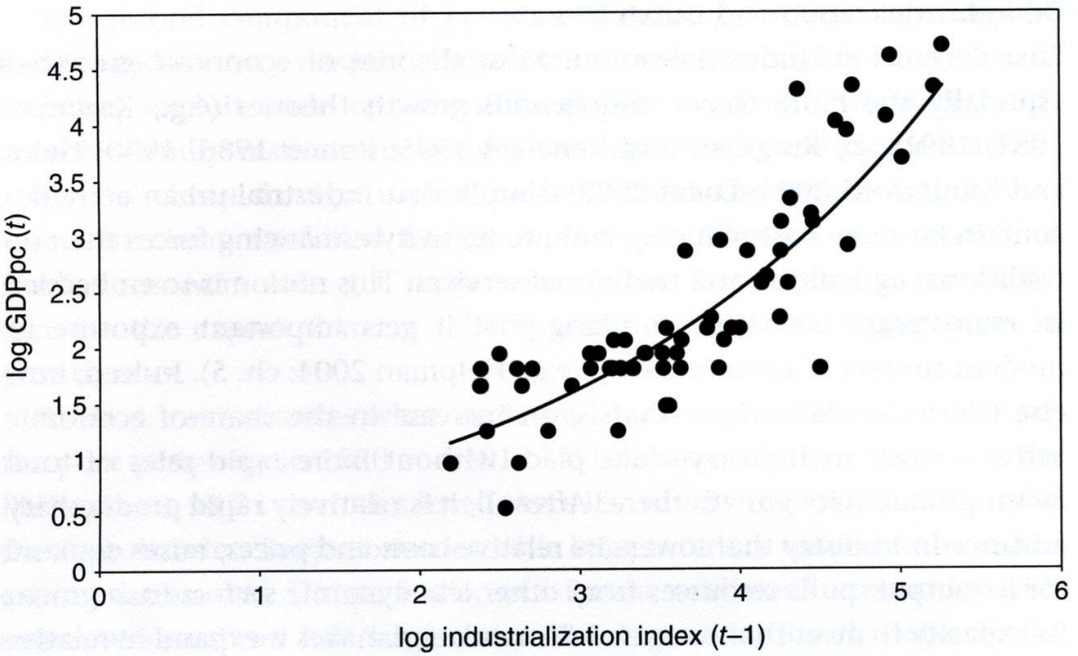
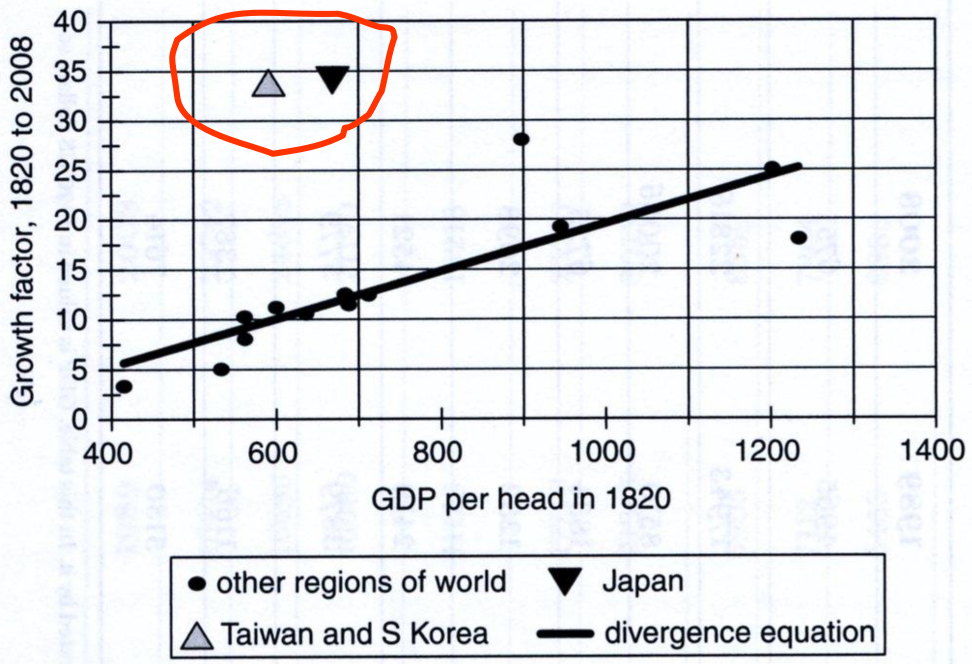


Figure 4.1
Do industrial countries get richer?
Source: Data from Bairoch (1982: table 4, p. 281) and Maddison (2001: tables A1–A3, pp. 185, 195, 215)

The plot shows the correlation, both in logs, of current GDP per capita (1820 -1950: Maddison), and past levels of industrialization per capita (50 or 70 years earlier: Bairoch).

Reference; Jeffrey G. Williamson, “ Trade and Poverty” MIT Press, 2011, p 50

The Great Divergence

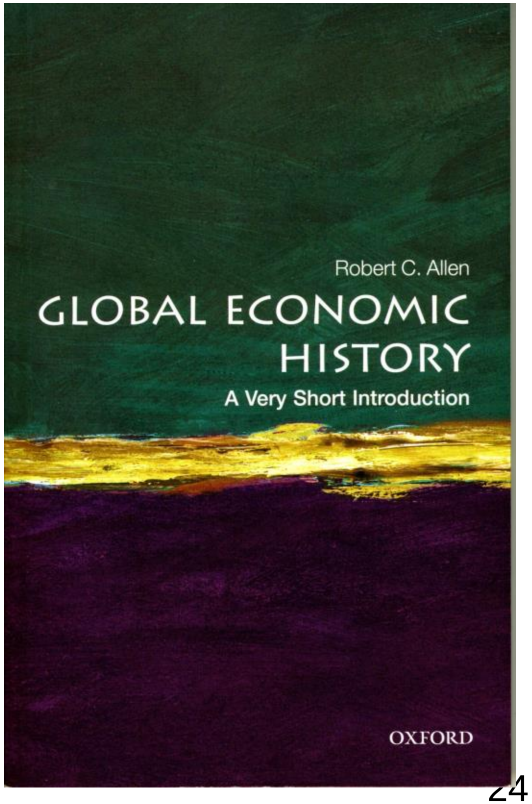


1. The great divergence

R.C. Allen 2011

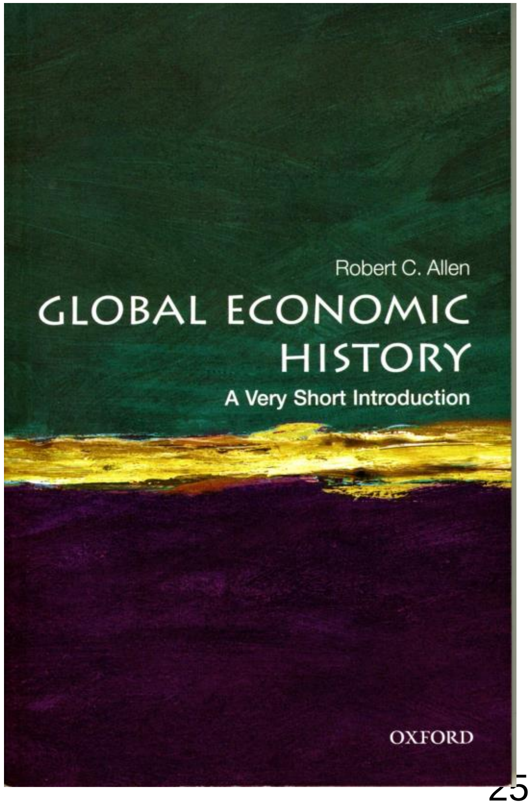
How do you join the developed?

- “Big Push Industrialization”
  - – Do everything at once
  - – Trust
  - – Planning Authority
  - – Then Transition…
- Required GDP growth
  - – ~6% over 60years



How do you join the developed?

- “Big Push Industrialization”
  - Japan
  - South Korea
  - Taiwan
- Less successful
  - Russia
  - South America

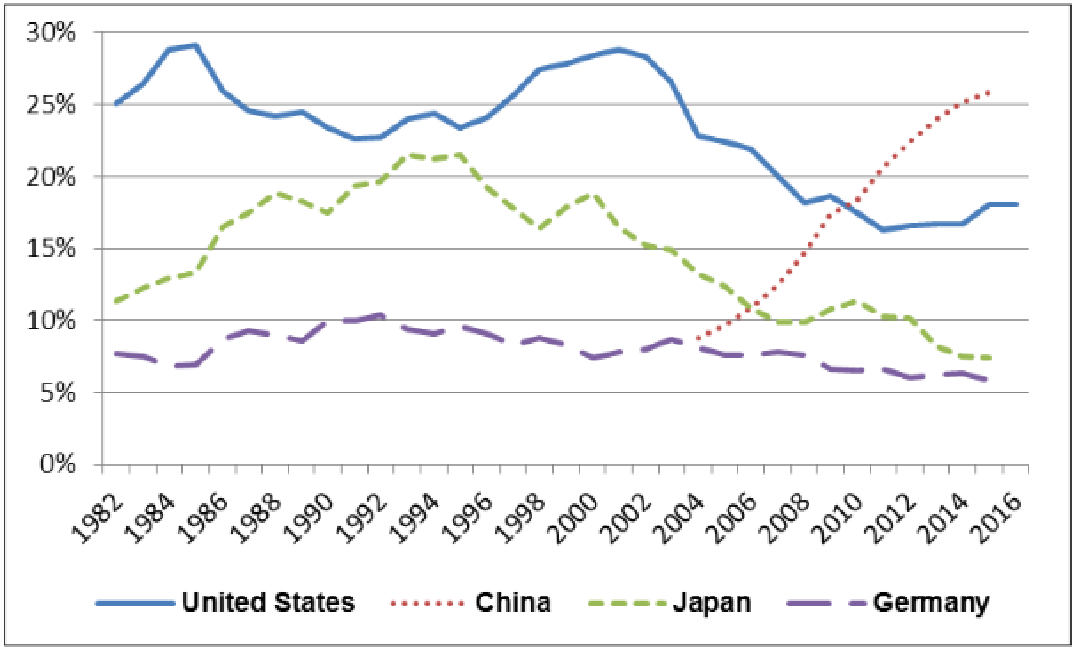


The Importance of Manufacturing for Economic Development

- The rise of China and Manufacturing

Figure 2. Selected Countries' Shares of Global Manufacturing Value Added

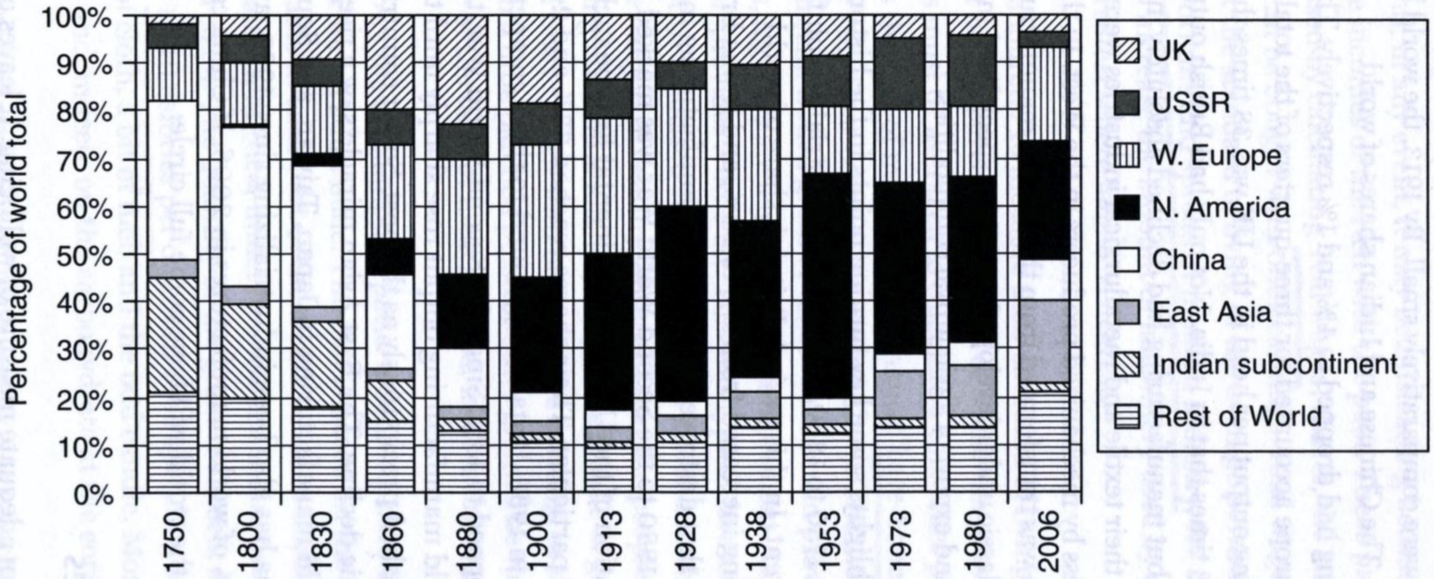
Calculated in current U.S. dollars



Source: U.N. National Accounts Main Aggregates Database, value added by economic activity, at current prices—U.S. dollars.

Marc Levinson,
Cong. Res. Ser.
2018

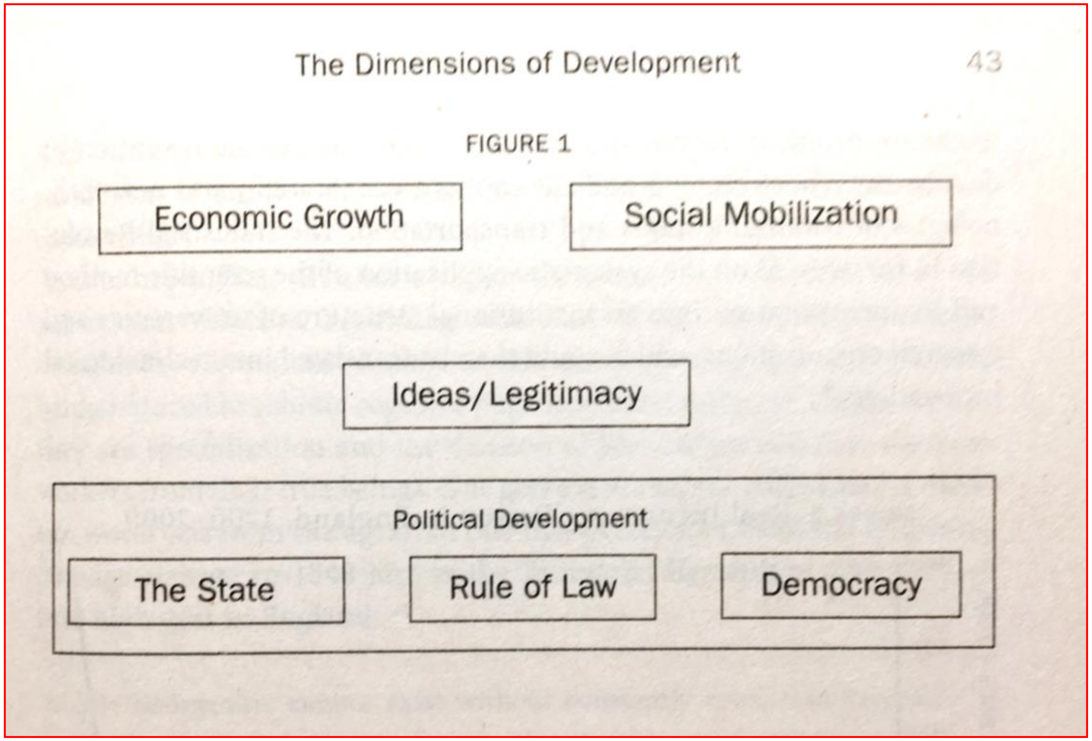
Global Mfg Shares 1750-2006



2. Distribution of world manufacturing

R.C. Allen 2011

The Role of Economic Growth in Political Development



The Dimensions of Development 43

FIGURE 1

Economic Growth

Social Mobilization

Ideas/Legitimacy

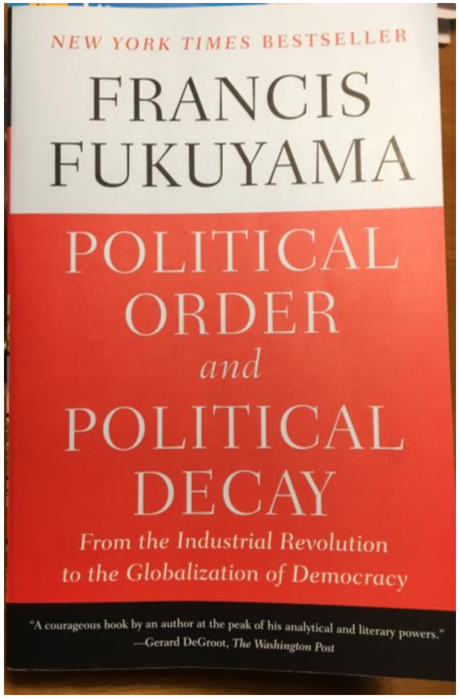
Political Development

The State

Rule of Law

Democracy

Ref. p 43



NEW YORK TIMES BESTSELLER

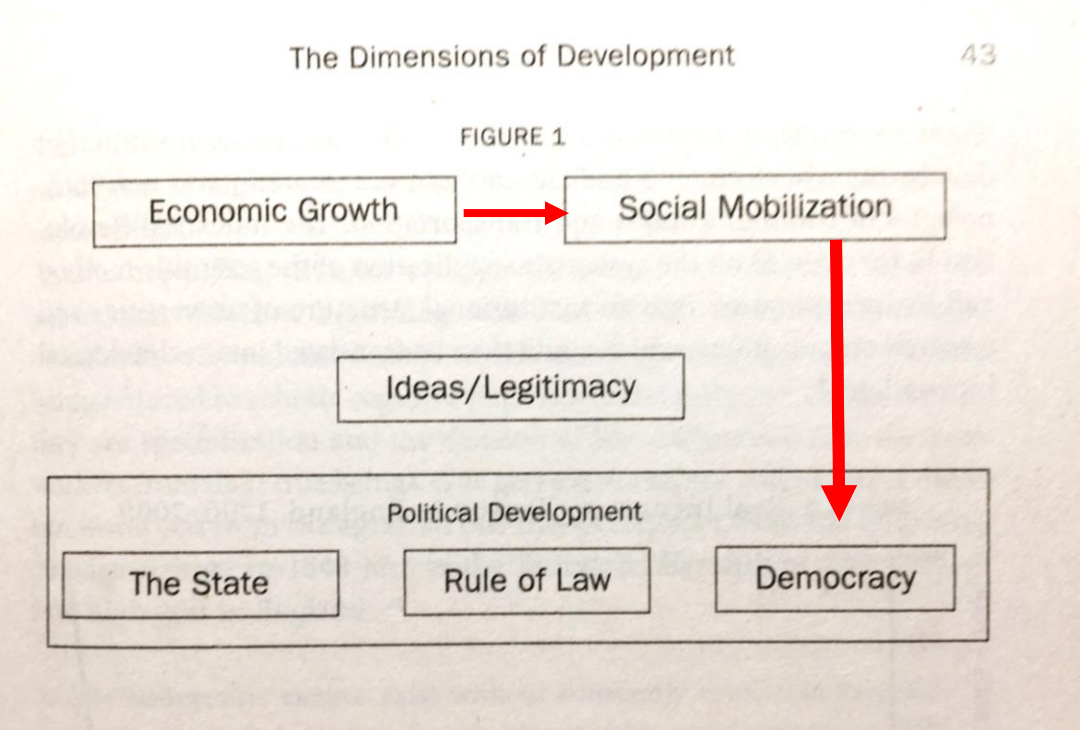
FRANCIS
FUKUYAMA

POLITICAL
ORDER
and
POLITICAL
DECAY

From the Industrial Revolution
to the Globalization of Democracy

"A courageous book by an author at the peak of his analytical and literary powers."
—Gerard DeGroot, *The Washington Post*

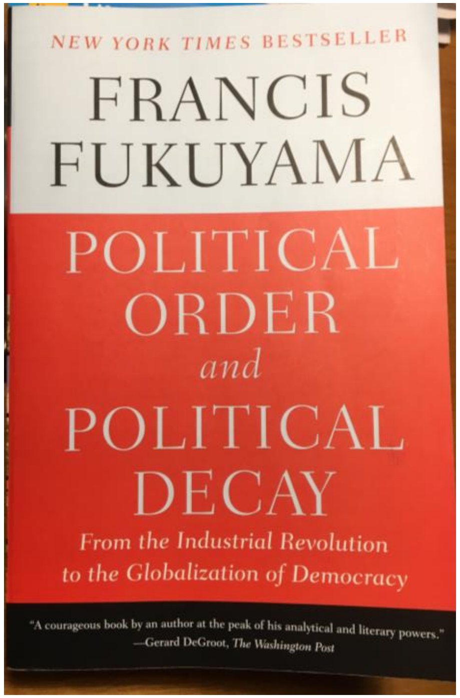
How Democracy might develop…



The Dimensions of Development 43

FIGURE 1

Ref. p 43



NEW YORK TIMES BESTSELLER

FRANCIS
FUKUYAMA

POLITICAL
ORDER
and
POLITICAL
DECAY

*From the Industrial Revolution
to the Globalization of Democracy*

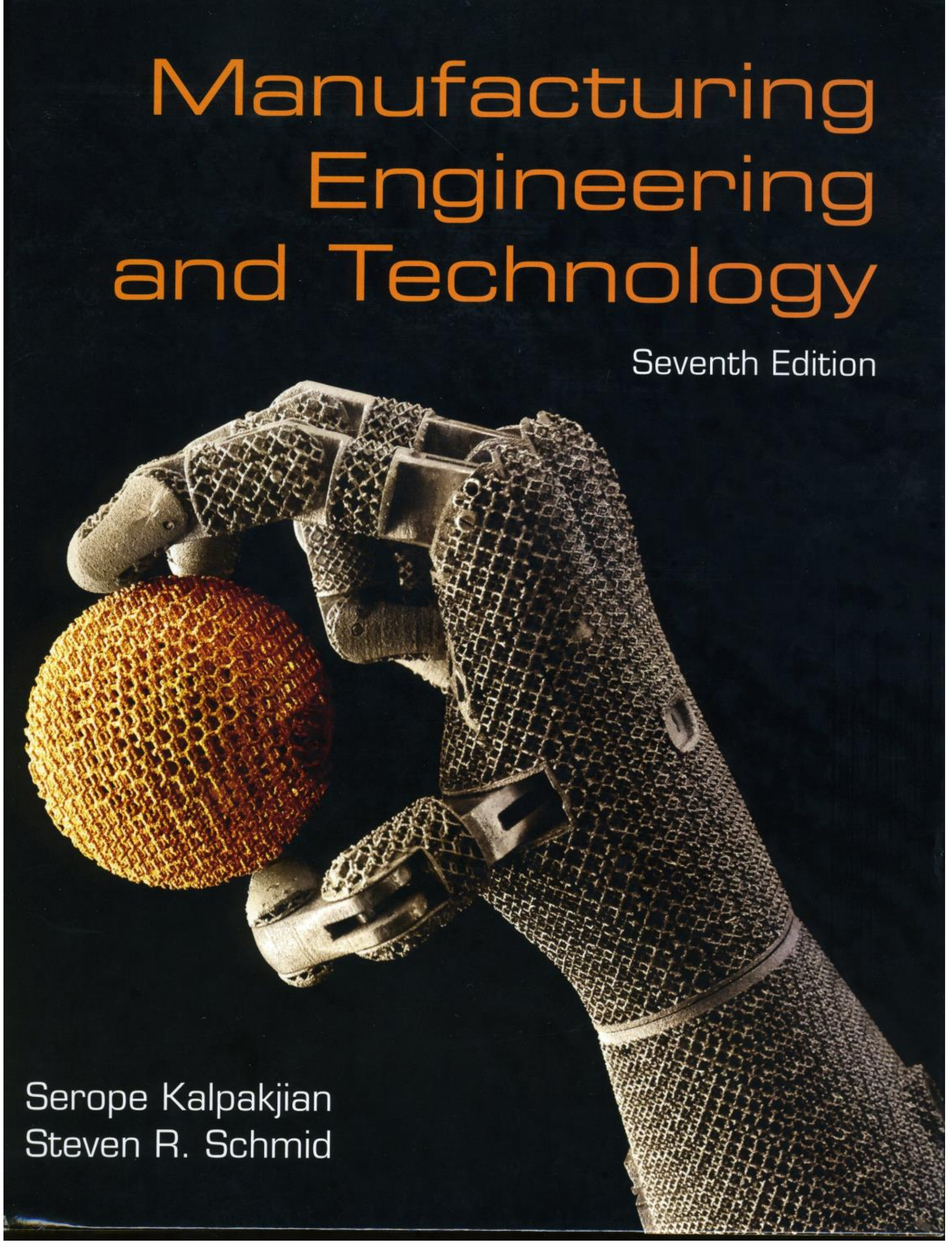
"A courageous book by an author at the peak of his analytical and literary powers."
—Gerard DeGroot, *The Washington Post*

The Future of Manufacturing

- Technology development
- Social and Political Environment
- The interaction between the two

Technology Development:

- Digital Mfg
- A.I.
- Integrated sensors
- blockchain
- 3D Printing
- Automation
- Industry 4.0
- New Products

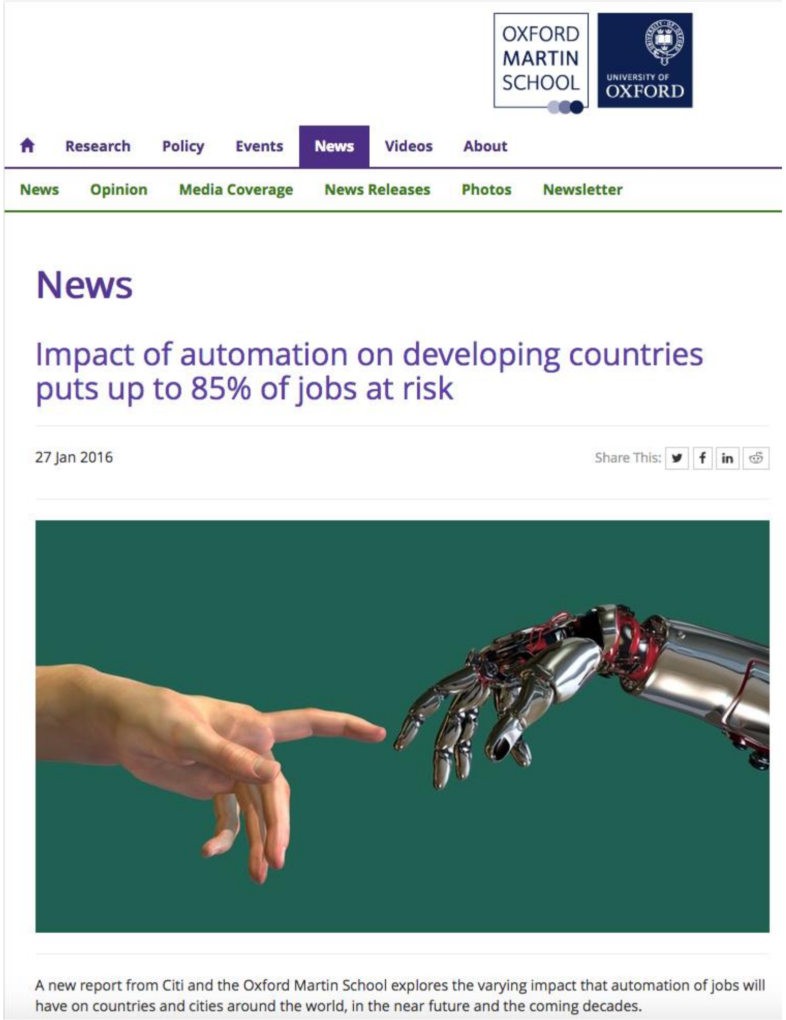


Manufacturing Engineering and Technology

Seventh Edition

Serope Kalpakjian
Steven R. Schmid

Future trends: Jobs & Growth

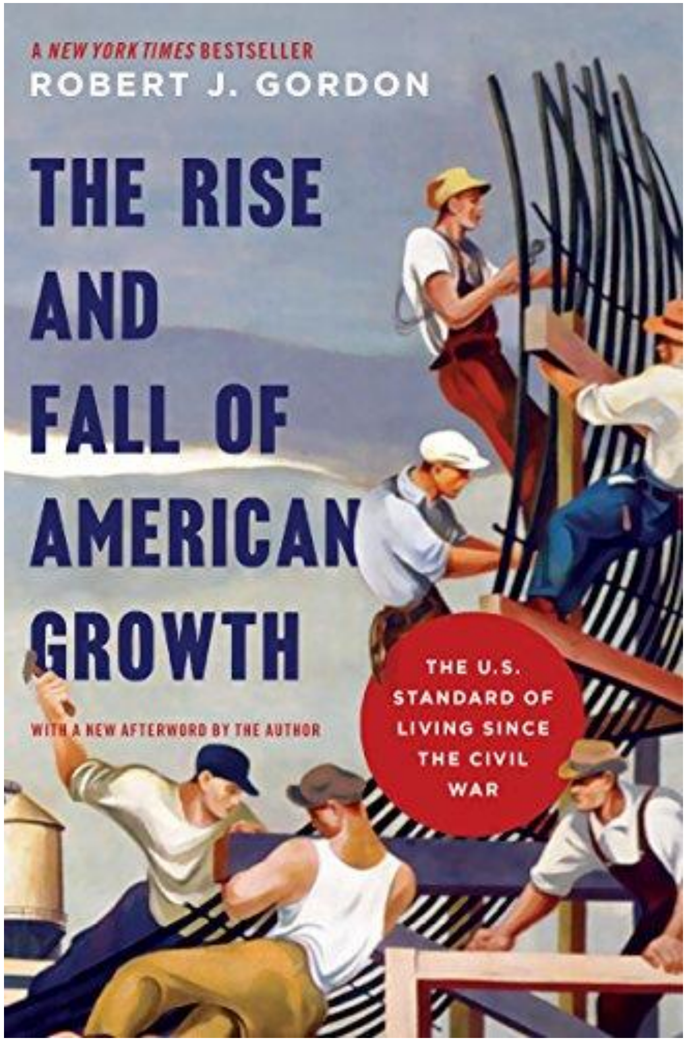


News

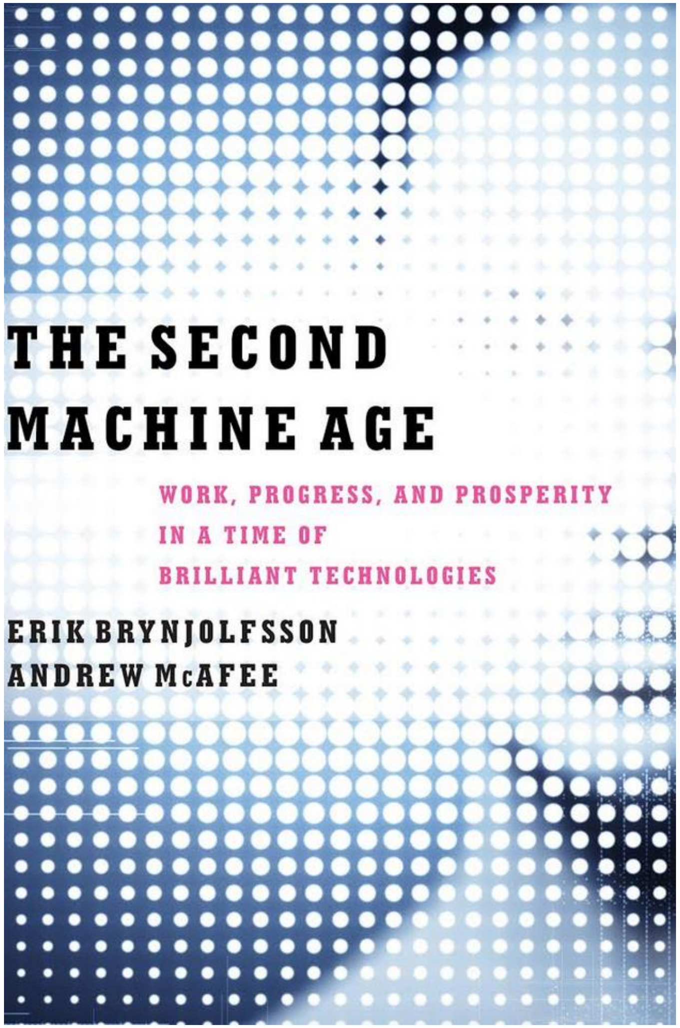
Impact of automation on developing countries puts up to 85% of jobs at risk

27 Jan 2016

A new report from Citi and the Oxford Martin School explores the varying impact that automation of jobs will have on countries and cities around the world, in the near future and the coming decades.



Future trends: “the bounty & the spread”

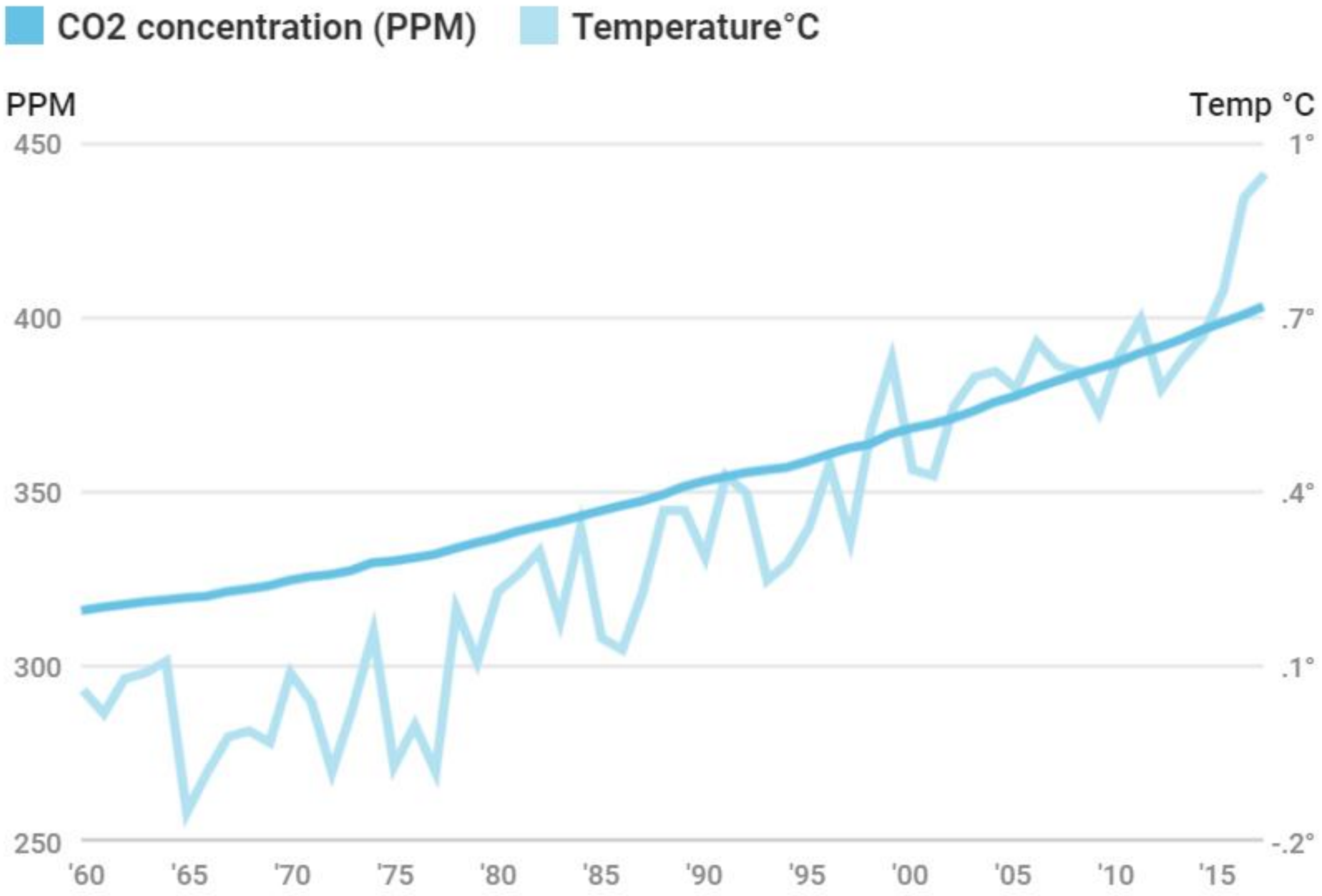


THE SECOND MACHINE AGE

WORK, PROGRESS, AND PROSPERITY IN A TIME OF BRILLIANT TECHNOLOGIES

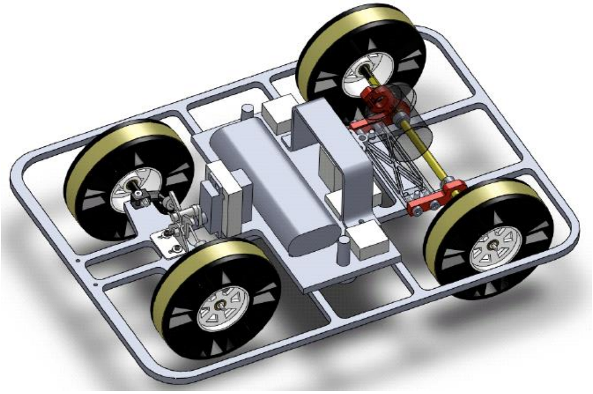
ERIK BRYNJOLFSSON
ANDREW McAFEE

The Environment: Climate Change

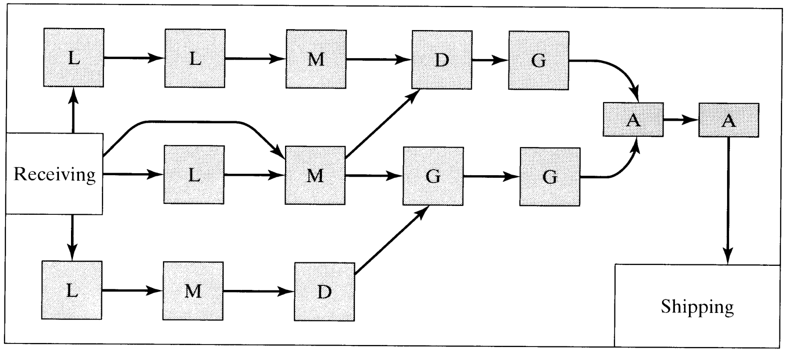


The Nuts and Bolts of 2.810

Processes



Project



Systems

Basic Concepts for 2.810

1. Manufacturing Processes

- Abstraction and trends
- Performance Attributes
- Physics

Manufacturing processes, …

MACHINING PROCESSES

SINGLE POINT MACHINING
- TURNING
- BORING
- FACING
- FORMING
- SHAPING,PLANNING

MULTIPOINT MACHINING
- DRILLING
- MILLING
- SAWING, FILING
- BROACHING, THREAD CUTTING

GRINDING
- SURFACE GRINDING
- CYLINDRICAL GRINDING
- CENTERLESS GRINDING
- INTERNAL GRINDING
- FORM GRINDING

ABRASIVE WIRE CUTTING
HONING
LAPPING
ULTRASONIC MACHINING
BUFFING, POLISHING
URNISHING
TUMBLING
GRIT BLASTING

CHEMICAL MACHINING
- ENGRAVING
- CHEMICAL MILLING
- CHEMICAL BLANKING

ELECTROCHEMICAL MACHINING
ELECTRICAL DISCHARGE MACHINING
LASTER MACHINING
ELECTRON BEAM MACHINING
PLASMA-ARC CUTTING
FLAME CUTTING, WATER JET CUTTING

DEFORMATION PROCESSES

OPEN-DIE FORGING
IMPRESSION-DIE FORGING
CLOSED-DIE FORGING
- PRECISION OR FLASHLESS FORGING
- COINING
- HEADING, PIERCING, HUBBING, COGGING, FULLERING, EDGING, ROLL FORGING, SKEW ROLLING

ROLLING
- FLAT, RING, THREAD, GEAR, PIERCING

EXTRUSION
- DIRECT, INDIRECT HYDROSTATIC, IMPACT, BACKWARD

DRAWING
- ROD & WIRE, FLAT STRIP, TUBES

SWAGING

SHEARING
BENDING
- PRESS-BRAKE FORMING, ROLL FORMING TUBE FORMING

BEADING, FLANGING, HEMMING, SEAMING
STRECH FORMING
BULGING
DEEP DRAWING
PRESS FORMING
RUBBER FORMING
SPINNING
EXPLOSIVE FORMING
ELECTROHYDRAULIC FORMING
MAGNETIC-PULSE FORMING
SUPERPLASTIC FORMING

METAL CASTING AND POWDER PROCESSES

CASTING
CASTING OF INGOTS
CONTINUOUS CASTING

SAND CASTING
SHELL MOLDING
SLURRY MOLDING
INVESTMENT CASTING (LOW-WAX PROCESS)
EVAPORATIVE CASTING
DIE CASTING
(GRAVITY-FEED, PRESSURIZED…)
CENTRIFUGAL CASTING
SQUEEZE CASTING
RHEOCASTING

CRYSTAL GROWING
- CRYSTAL-PULLING
- ZONE MELTING

Electro forming
Plasma Spraying

POWDER METALLURGY
PRESSING
ISOSTATIC PRESSING
SINTERING

JOINING PROCESSES

MECHANICAL JOINING
- BOLTS, SCREWS, RIVETS

SOLID-STATE WELDING
- DIFFUSION, FORGING, FRICTION, DEFORMATION

LIQUID STATE WELDING
- RESISTANCE WELDING
- ARC WELDING
- THERMAL WELDING

HIGH-ENERGY BEAM WELDING
- ELECTRONIC BEAM, LASER

LIQUID-SOLID STATE BONDING
- BRAZING
- SOLDERING

ADHESIVE BONDING
- PLASTICS AND COMPOSITES JOINING (MECHANICAL, HEATING, SOLVENTS, ULTRASONICS…)

POLYMER PROCESSES

EXTRUSION
FIBER SPINNING
CALANDERING
FILM BLOWING
COATING
(MELTS, SOLUTION, PLASMA, ELECTROSTATIC, PLASTISOL, UV CURABLE…)
BLOW MOLDING
INJECTION MOLDING
REACTION INJECTION MOLDING (RIM)
COMPRESSION MOLDING
TRANSFER MOLDING
CASTING
THERMOFORMING
ROTATIONAL MOLDING
SOLID STATE FORMING

MACHINING
ETCHING SOLVENT PROCESSING
FOAMING
BONDING
IMPREGNATING
PAINTING

COMPOSITES PROCESSES

(POLYMER COMPOSITES)

PULTRUSION
FILAMENT WINDING
PULL FORMING
BRAIDING
AUTOCLAVE MOLDING
COMPRESSION MOLDING (SMC)
RESIN TRANSFER MOLDING
AUTOCOMP MOLDING
HAND LAY-UP
SPRAY-UP
AUTOMATIC TAPE LAY-UP
STAMPING
DIAPHGRAM FORMING
INJECTION MOLDING
(FILLED THERMOPLASTICS, BMC…)
REINFORCED REACTION INJECTION MOLDING (RRIM)

(METAL MATRIX COMPOSITES)

HOT PRESSURE BONDING
HOT ISOSTATIC PRESSING
LIQUID METAL INFILTRATION
ELECTRODEPOSITION
PLASMA SPRAY DEPOSITION

CERAMICS PROCESSES

POWER PROCESSES
- CONSOLIDATION
- SINTERING

MELT PROCESSES
- CRYSTALLINE MATERIALS (SILICON)
- GLASSES
- DRAWING, CASTING, BLOWING, TEMPERING (OPTICAL & STRUCTURAL FILTERS)
- COATING

SOL-GEL CERAMICS PROCESSING

MICROELECTRONICS PROCESSING

CRYSTAL GROWTH
- CZOCHRALSKI CRYSTAL GROWTH
- FLOAT-ZONE CRYSTAL GROWTH

WAFER PROCESSING
- SLICING, ETCHING, POLISHINNG

SURFACE PROCESSES
- CHEMICAL VAPOR DEPOSITION (CVD)
- EPITAXIAL FILM GROWTH
- POLY CRYSTALLINE FILM GROWTH
- $S_1 0_2$ FILMS
- OTHER (DIELECTRICS, METALS)

OXIDATION
- ION IMPLANTATION
- PHYSICAL VAPOR DEPOSITION
- SPUTTERING
- EVAPORATION

LITHOGRAPHY
- PHOTORESIST
- ELECTRON BEAM, X-RAY, ION BEAM LITHOGRAPHY

WET ETCHING
- CHEMICAL

DRY ETCHING
- PLASMA
- SPUTTER
- REACTIVE ION

PACKAGING
- DICING
- DIE ATTACHMENT
- WIRE BONDING
- ENCAPSULATION

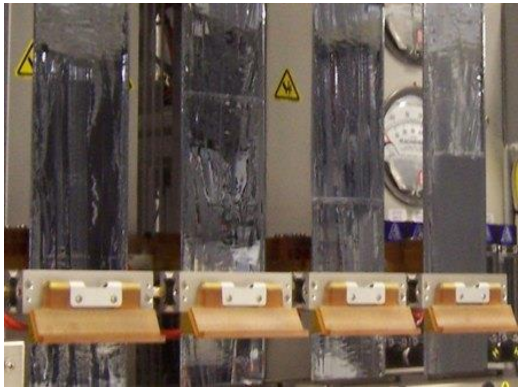
172 processes + rapid prototyping + etc, etc

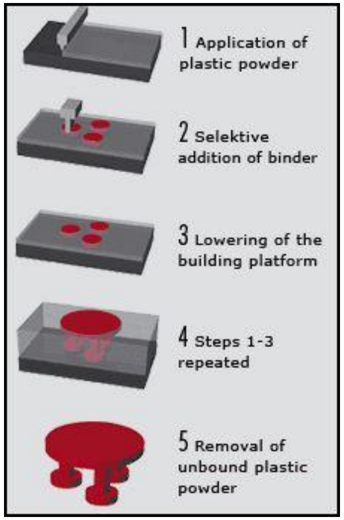
ADDITIVE MANUFACTURING TECHNOLOGIES

- **Vat photopolymerization**
  - Cured with laser: **SLA** Stereolithography — Plastic — 3D Systems, formlabs, DWS
  - Cured with projector: **DLP** Digital Light Processing — Plastic — envisionTEC, B9Creator
  - Cured with LED & oxygen: **CDLP** Continuous Digital Light Processing — Plastic — carbon3D, envisionTEC
- **Material extrusion**
  - **FDM** Fused Deposition Modeling — Composite, Plastic
    - Plastic: stratasys, Ultimaker, MakerBot, zortrax, PRUSA PRINTERS, printrbot, LULZBOT
    - Composite (CFF): Markforged
- **Material jetting**
  - Cured with UV light: **MJ** Material Jetting — Plastic — stratasys, 3D Systems
  - Cured with heat: **NPJ** NanoParticle Jetting — Metal — XJET
  - Milled to form: **DOD** Drop On Demand — Wax — Solidscape
- **Binder jetting**
  - Joined with bonding agent: **BJ** Binder Jetting — Gypsum, Sand; Metal
    - Gypsum, Sand: 3D Systems, voxeljet
    - Metal: ExOne
- **Powder bed fusion**
  - Fused with agent and energy: **MJF** Multi Jet Fusion — Plastic — hp
  - Fused with laser:
    - **SLS** Selective Laser Sintering — Plastic — eos, 3D Systems, SINTERIT, Sintratec
    - **DMLS / SLM** Direct Metal Laser Sintering Selective Laser Melting — Metal — eos, 3D Systems, SLM, RENISHAW, CONCEPTLASER, Additive Industries
  - Fused with electron beam: **EBM** Electron Beam Melting — Metal — arcam
- **Direct energy deposition**
  - Fused with laser: **LENS** Laser Engineering Net Shape — Metal — OPTOMEC
  - Fused with electron beam: **EBAM** Electron Beam Additive Manufacturing — Metal — SCIAKY INC
- **Sheet lamination**
  - **LOM** Laminated Object Manufacturing — Composite, Paper
    - Paper: Mcor
    - Composite: envisionTEC, IMPOSSIBLE OBJECTS

Find out more at **www.3dhubs.com/what-is-3d-printing**

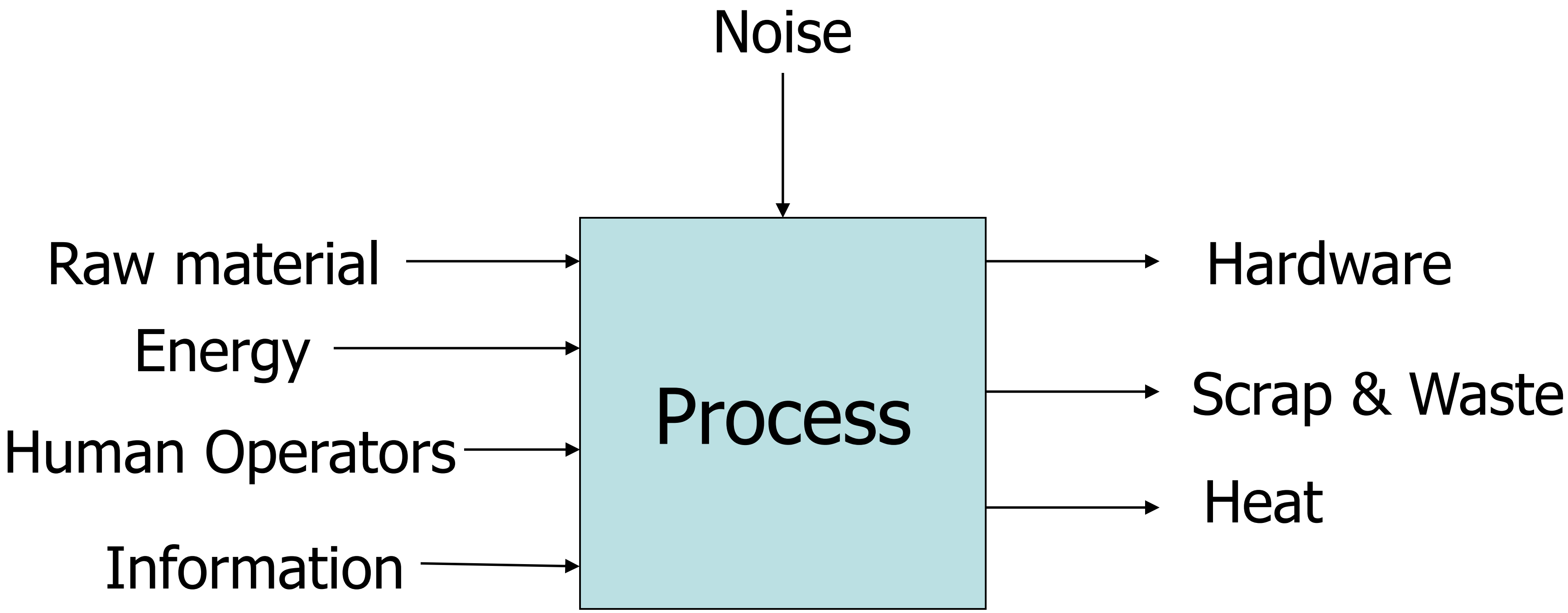
3D HUBS





Some Processes developed out of LMP (bldg 35)

Abstraction of a Mfg Processes



Process Classification

- Materials
- Machines
- Applications

vs

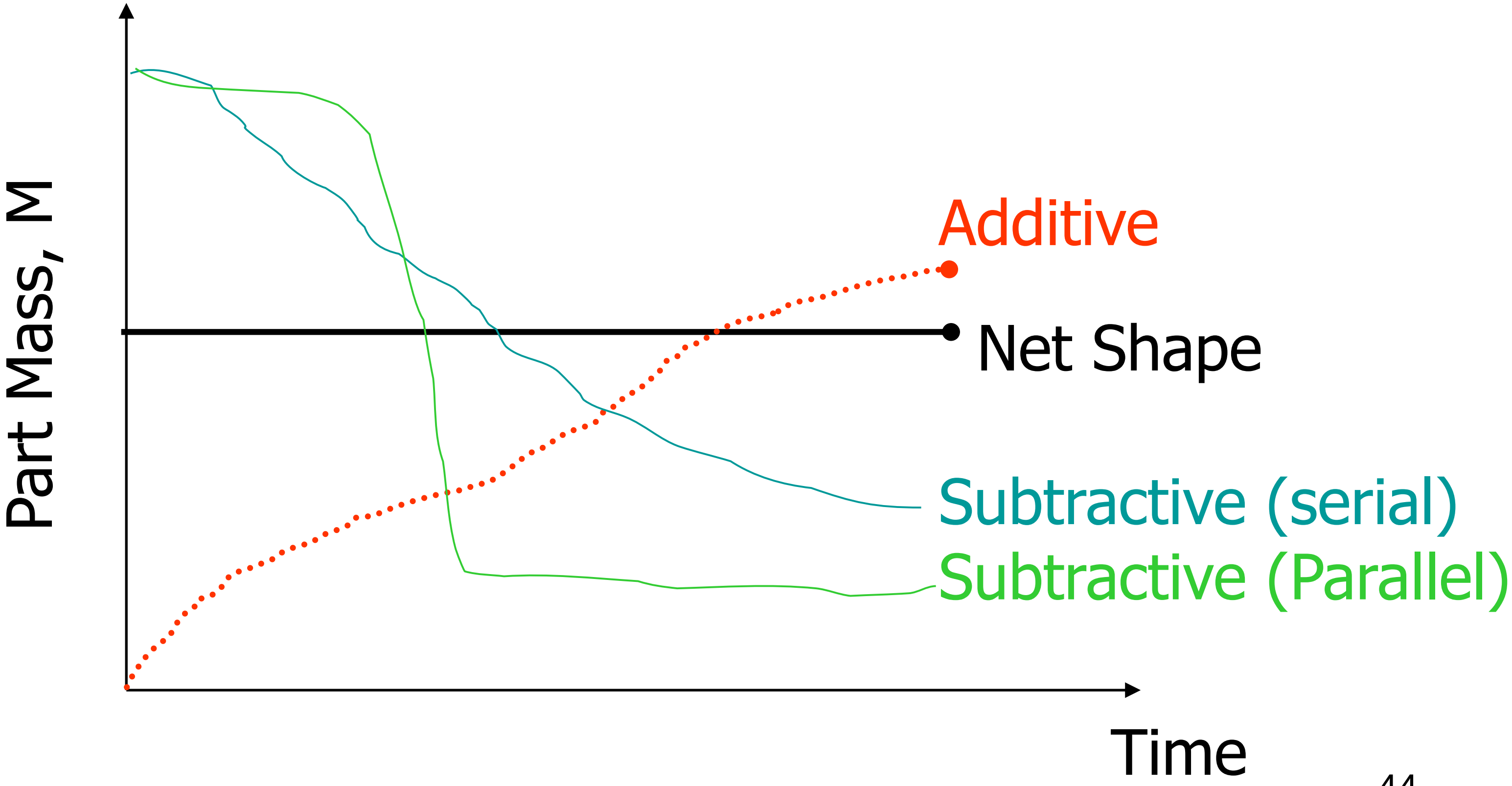
- Geometry
- Time
- Energy

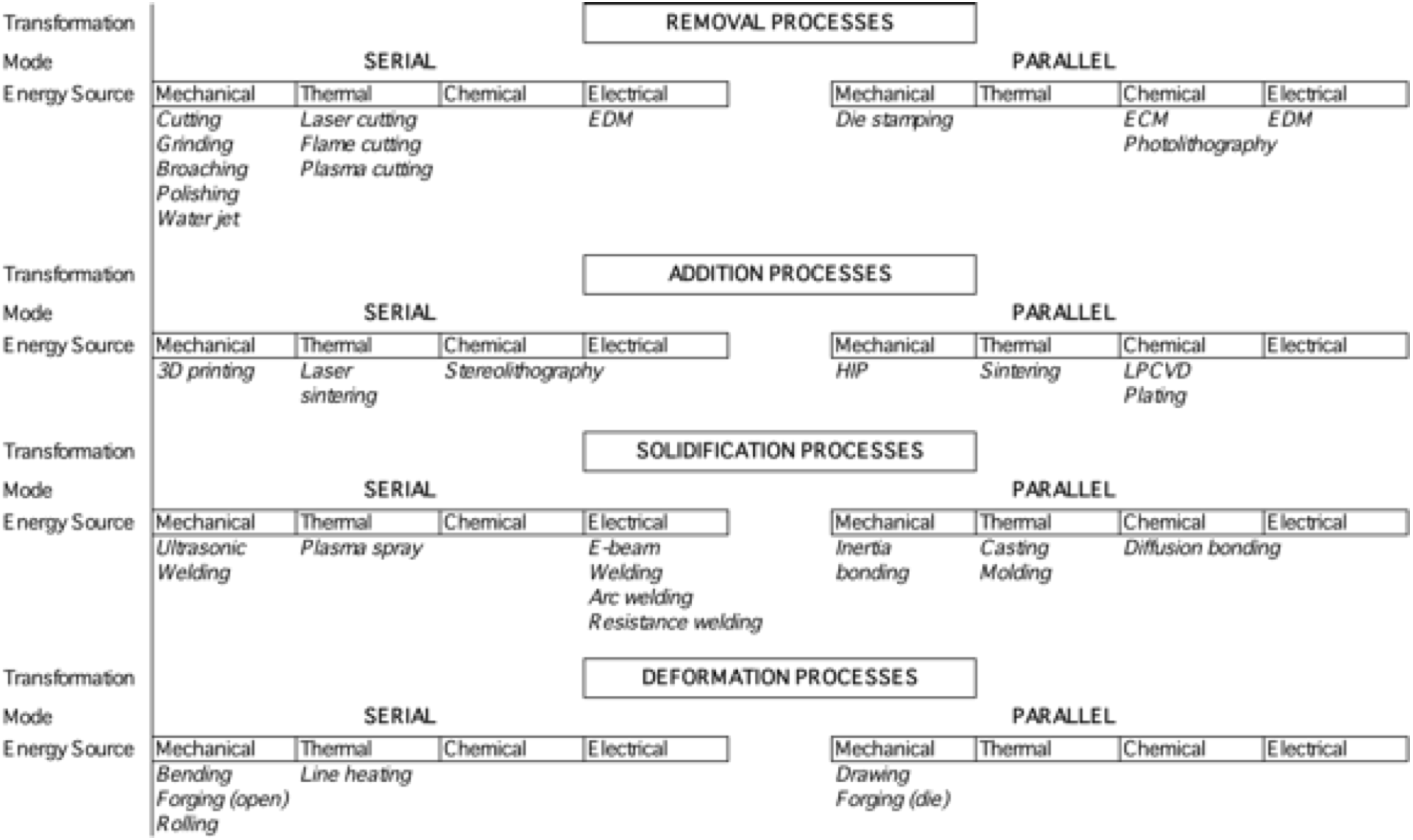
Process Classification

- Geometrical transformation
  - – Subtractive / Additive / Net
- Time sequence
  - – Serial / Parallel
- Energy domain
  - – Mechanical / Thermal / Chemical / Electrical

See "Manufacturing Processes and Process Control," David E. Hardt

Geometrical classification





Transformation	REMOVAL PROCESSES							
Mode	SERIAL				PARALLEL			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Cutting *Grinding* *Broaching* *Polishing* *Water jet*	*Laser cutting* *Flame cutting* *Plasma cutting*		*EDM*	*Die stamping*		*ECM* *Photolithography*	*EDM*

Transformation	ADDITION PROCESSES							
Mode	SERIAL				PARALLEL			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	3D printing	*Laser sintering*	*Stereolithography*		*HIP*	*Sintering*	*LPCVD* *Plating*	

Transformation	SOLIDIFICATION PROCESSES							
Mode	SERIAL				PARALLEL			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Ultrasonic Welding	*Plasma spray*		*E-beam Welding* *Arc welding* *Resistance welding*	*Inertia bonding*	*Casting* *Molding*	*Diffusion bonding*	

Transformation	DEFORMATION PROCESSES							
Mode	SERIAL				PARALLEL			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Bending *Forging (open)* *Rolling*	*Line heating*			*Drawing* *Forging (die)*			

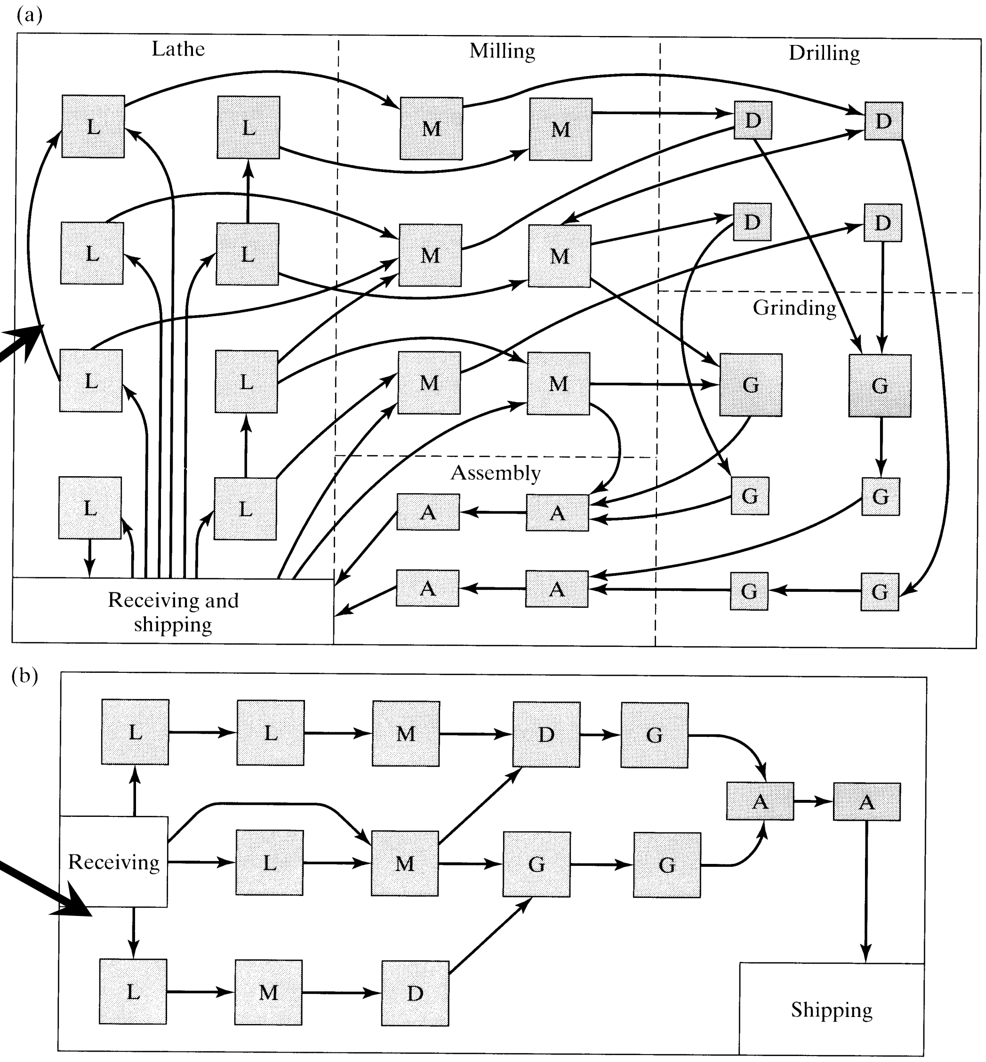
* Taken from “Manufacturing Processes and Process Control,” David E. Hardt

Basic Concepts for 2.810

2. Manufacturing Systems

- Physical part
- Required machines
- Process steps
- Equipment arrangements
- Tools, History

Mfg. System Designs; (a) job shop (b) flow shop



Manufacturing Systems

- Configurations
- Analysis tools (time performance)
- Historical development
- Current practice
- Future trends

From part to system

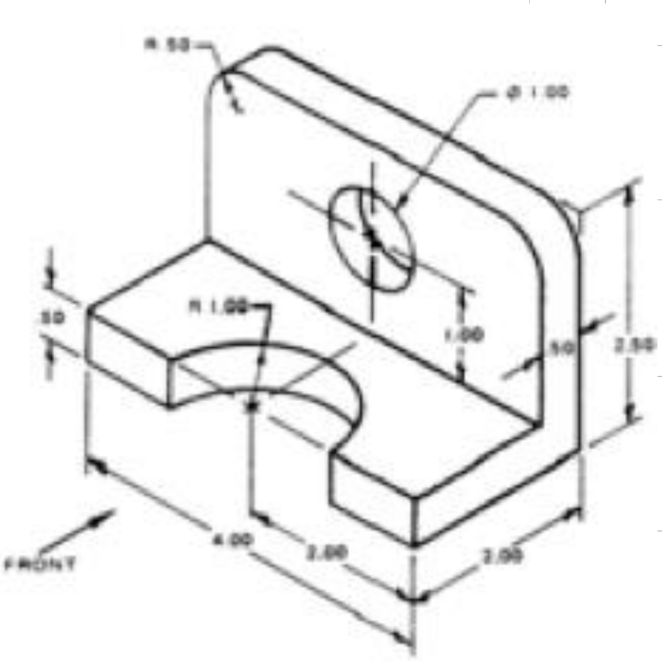
Physical Part	Process Steps	System Design
Shape, Materials, Tolerances	Equipment, Tools, Procedures	Equipment arrangement, Flows Skill Levels, other Resources
Representation	Process Plan -	Cell or system-

Process Planning

- Identify machines
- Tools
- Settings
- Steps required to produce a geometry to tolerance
- Time estimation

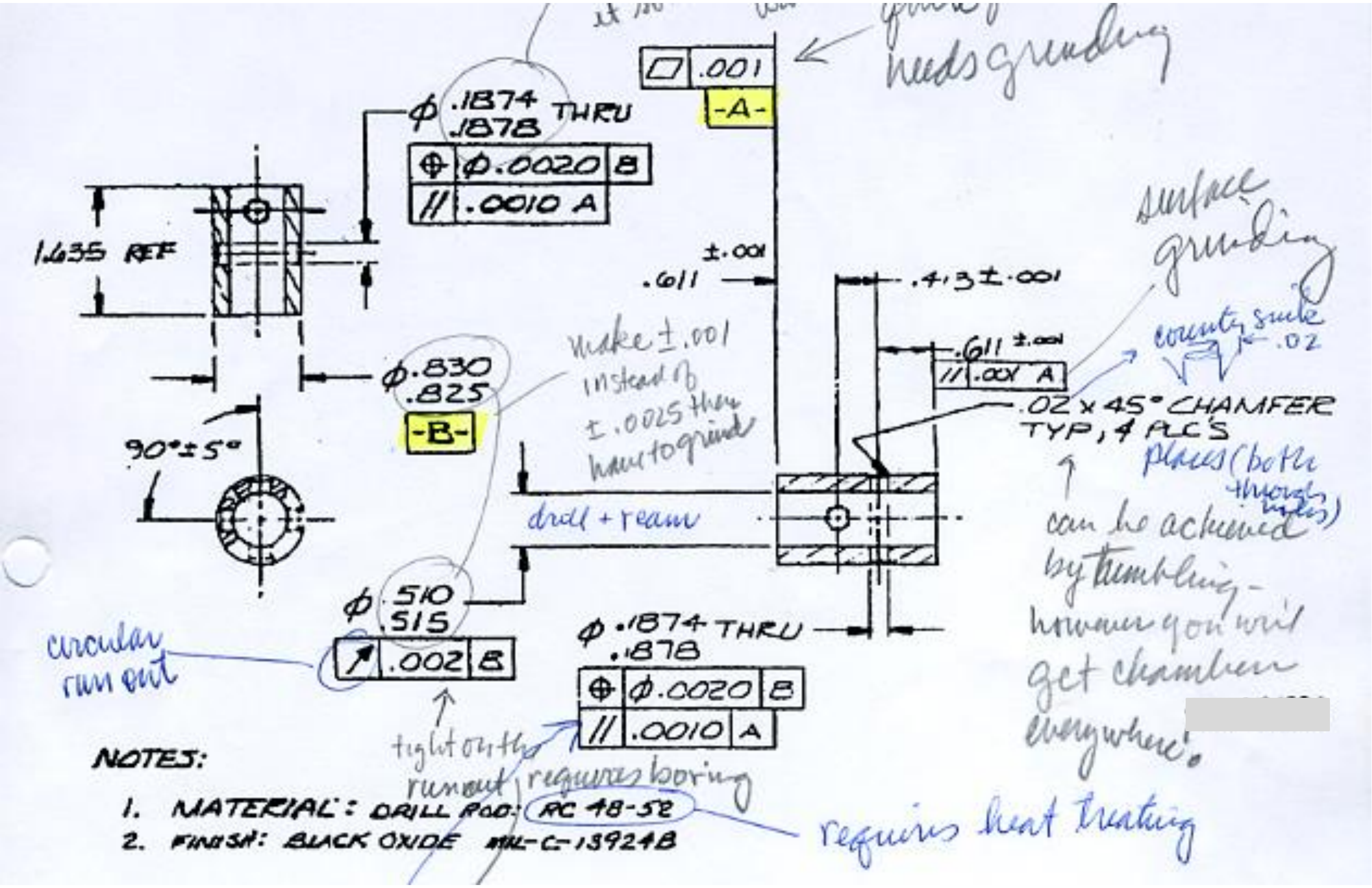
Process Plan Time Estimation

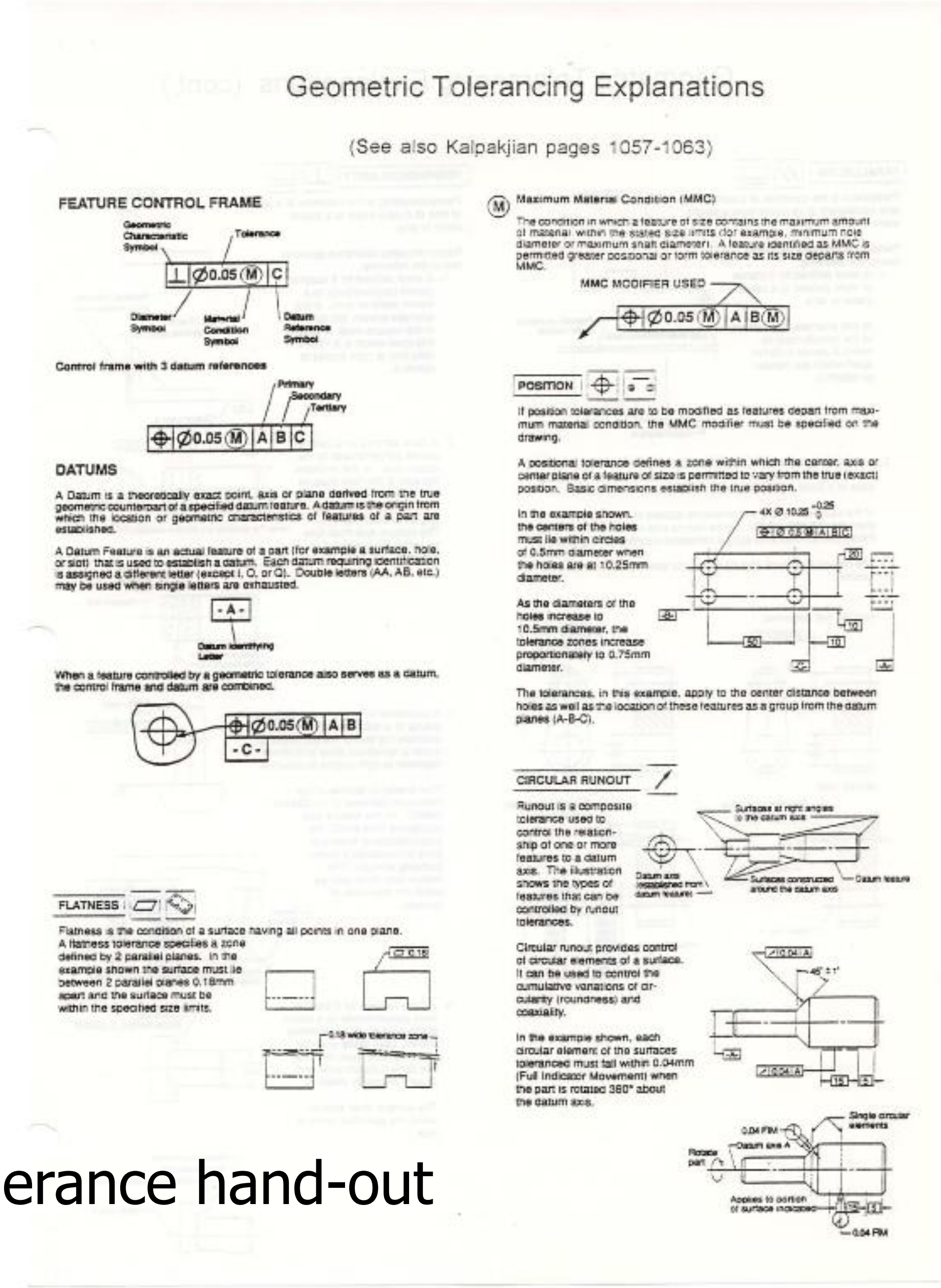
Rod Support



#	Machine	Operation (V = Volume A = Area P = Perimeter)	Fixture	Tool Change	Run (R = Rough F = Finish)	Deburr Inspect Measure
10	1	Saw stock to ~ 4.125” A = 5.625 in2 P = 9 in	0.23	–	2.02	0.30D 0.05I
20	2	Mill two ends to length 4” V = 0.703 in3 A = 11.25 in2 P = 19 in	0.20 0.20	2	0.13R 0.75F	0.63D 0.05I 0.13M
30	2	Mill width to 2” V = 2.5 in3 A = 10 in2 P = 13 in	0.20	–	0.46R 0.67F	0.43D 0.05I 0.13M
	2	Mill out 2”x1.5”x4” V = 12 in3 A = 14 in2 P = 15 in	–	–	2.19R 0.93F	0.50D 0.05I 0.13M 0.13M
	2	Drill hole 1” diameter -Center drill -Pilot drill 1/2” -Pilot drill 63/64” -Ream	0.20	2 2 2 2	0.03 0.05 0.04 0.01	0.21D 0.05I 0.17M
	2	Bore 1” radius V = 0.79 in3 A = 1.57 in2 P = 7.28 in	0.20	2	0.96R 0.10F	0.24D 0.05I 0.06M
	3	Sand 0.5” radii V = 0.05 in3 A = 0.79 in2 P = 3.14 in	0.08	–	0.20R 0.21F	0.10D 0.05I 0.06M 0.06M
		Totals:	1.31	12.00	8.75	3.63

Engineering Drawing; Connecting Link





Geometric Tolerancing Explanations

(See also Kalpakjian pages 1057-1063)

FEATURE CONTROL FRAME

Control frame with 3 datum references

DATUMS

A Datum is a theoretically exact point, axis or plane derived from the true geometric counterpart of a specified datum feature. A datum is the origin from which the location or geometric characteristics of features of a part are established.

A Datum Feature is an actual feature of a part (for example a surface, hole, or slot) that is used to establish a datum. Each datum requiring identification is assigned a different letter (except I, O, or Q). Double letters (AA, AB, etc.) may be used when single letters are exhausted.

When a feature controlled by a geometric tolerance also serves as a datum, the control frame and datum are combined.

FLATNESS

Flatness is the condition of a surface having all points in one plane. A flatness tolerance specifies a zone defined by 2 parallel planes. In the example shown the surface must lie between 2 parallel planes 0.18mm apart and the surface must be within the specified size limits.

Ⓜ **Maximum Material Condition (MMC)**

The condition in which a feature of size contains the maximum amount of material within the stated size limits (for example, minimum hole diameter or maximum shaft diameter). A feature identified as MMC is permitted greater positional or form tolerance as its size departs from MMC.

POSITION

If position tolerances are to be modified as features depart from maximum material condition, the MMC modifier must be specified on the drawing.

A positional tolerance defines a zone within which the center, axis or center plane of a feature of size is permitted to vary from the true (exact) position. Basic dimensions establish the true position.

In the example shown, the centers of the holes must lie within circles of 0.5mm diameter when the holes are at 10.25mm diameter.

As the diameters of the holes increase to 10.5mm diameter, the tolerance zones increase proportionately to 0.75mm diameter.

The tolerances, in this example, apply to the center distance between holes as well as the location of these features as a group from the datum planes (A-B-C).

CIRCULAR RUNOUT

Runout is a composite tolerance used to control the relationship of one or more features to a datum axis. The illustration shows the types of features that can be controlled by runout tolerances.

Circular runout provides control of circular elements of a surface. It can be used to control the cumulative variations of circularity (roundness) and coaxiality.

In the example shown, each circular element of the surfaces toleranced must fall within 0.04mm (Full Indicator Movement) when the part is rotated 360° about the datum axis.

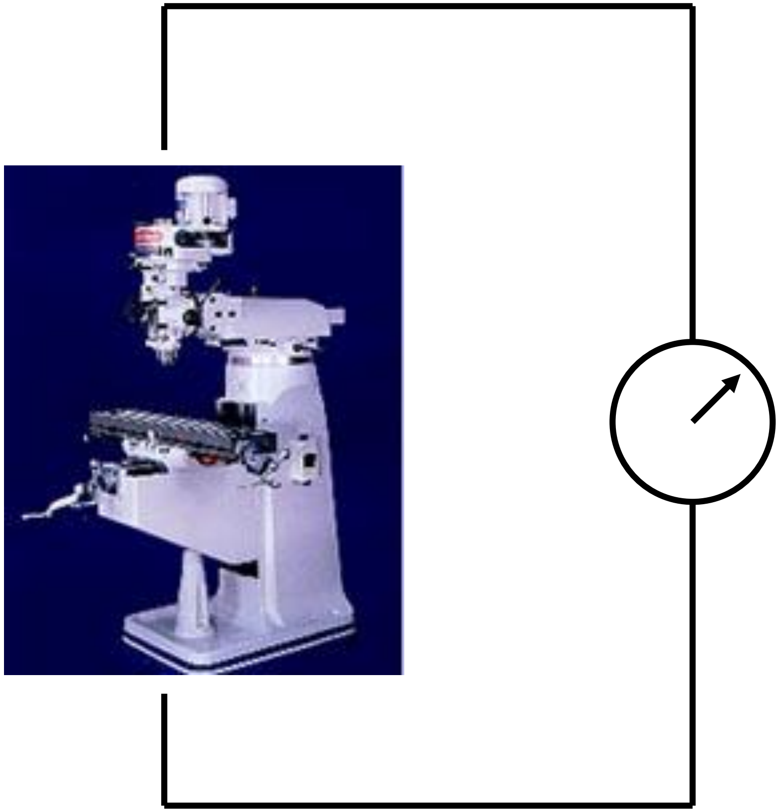
See Tolerance hand-out

Process Plan Time Estimate

Connecting Link

#	Machine	Operation (V = Volume A = Area P = Perimeter)	# Dims.	Fixture	Tool Change	Run (R = Rough F = Finish)
10	1	Face end Assume V = 0.075 in3	–	0.17	0.1	0.08
20		Turn diameter to 0.827” V = 0.105 in3	–	–	–	0.11
30		Turn diameter finish pass A = 23 in2	1	–	–	1.35
40		Center drill 0.512” dia.	–	–	0.1	0.05
50		Drill with 0.4688” drill	–	–	0.1	0.28
60		Bore to 0.512” V = 0.033 in3	1		0.1	0.05
70	2	Grind to exact length of 1.635” Assume V = 0.075 in3 A = 0.331 in2	1	0.04	–	0.11R 0.01F
80	3	Fixture in collet on indexer to drill holes V = 1.65 in3	–	0.17	–	–
90		Center drill 0.1875” hole	–	–	0.5	0.05
100		Drill to 11/64”	–	–	0.5	0.17
110		Ream to 0.1875”	2	–	0.5	0.06
120		Index part	–	0.1	–	–
130		Center drill 0.1875” hole	–	–	0.5	0.05
140		Drill to 11/64”	–	–	0.5	0.17
150		Ream to 0.1875”	4	–	0.5	0.06
160		Deburr all edges P = 10.77 in	–	–	–	0.72
		Totals:	9	0.48	3.40	3.32

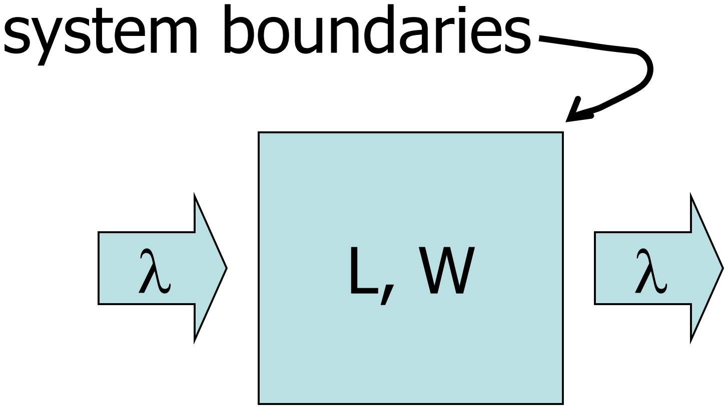
Performance measures



- Rate
- Time
- Cost
- Quality
- Flexibility
- Environment

See “Competitive Attributes…” T. Gutowski

Rate and Time



system boundaries

λ

L, W

λ

Little’s law: $L = \lambda W$ (all average values)

- L = units in system (inventory)
- λ = rate of material arrival
- W = time in system

Time at the Machine

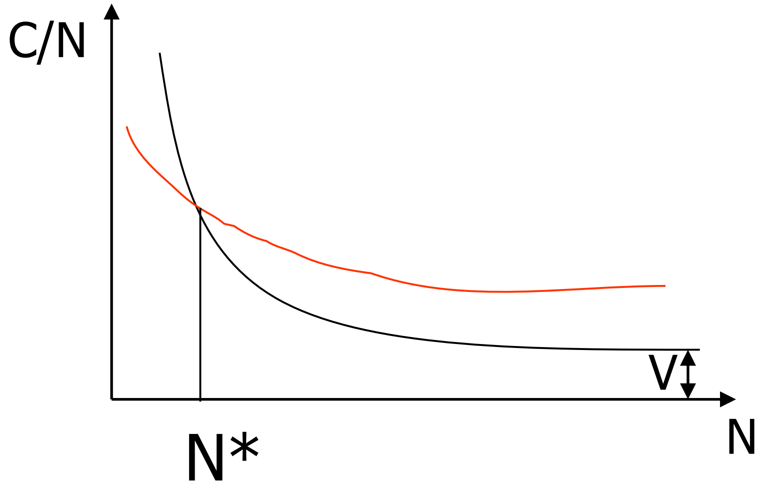
- Time at the machine
  - Set-up time,
  - Process time, (parallel, serial)
  - Multi-cavity tooling
  - Post processing Time
  - Machine Rate

Time for the Cell or Line

Multiple Machine Systems:

- Batch processing
- Continuous processing
- Bottlenecks and Balancing
- Waiting
- Buffers

Direct Costs



- Variable Costs:
  - Materials + Waste
  - Labor (time & skill level)
  - General Purpose Equip (time, capital, maintenance)
- Fixed Costs:
  - Dedicated Equipment (tooling…)

Direct Costs

Economies of scale

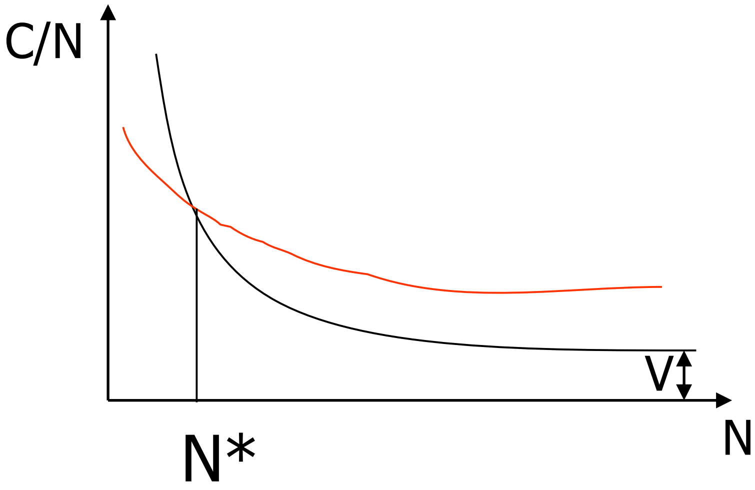
$C = F + V \times N$

C = Total cost

F = Fixed cost

V = Variable cost

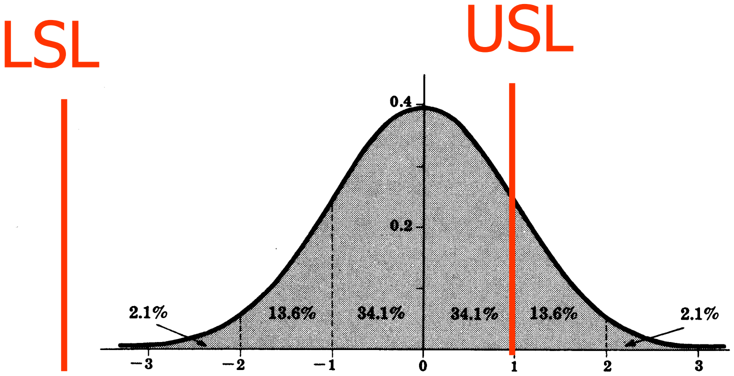
N = number of units



Quality

- Satisfied Customer (systems level)
- Deviation from target (process level)
    - Establishing the target (design)
    - Normal variation (process in control)
    - Observing deviation (SPC)

Quality



Normal distribution $N(0,1)$

Process Capability Index, C_p and C_{pk}

- $C_p = (USL-LSL) / 6\sigma$
  - – USL = Upper Specification Limit
  - – LSL = Lower Specification Limit
  - – σ = standard deviation of the process output
- USL and LSL are something specified by design
- The standard deviation is due to variation in the process

Flexibility

- Ability to accommodate different geometries, materials, production volumes, etc.
- Measured as Δ cost, Δ time, etc.

Environmental performance

- Process Level
- Product Level
- Life Cycle Assessment
- Enterprise Level
- Global Level

2.810 Project

- Form Teams
- Cooperate
- Manage
- Design
- Manufacture
- Test
- Compete
- Report and Evaluate

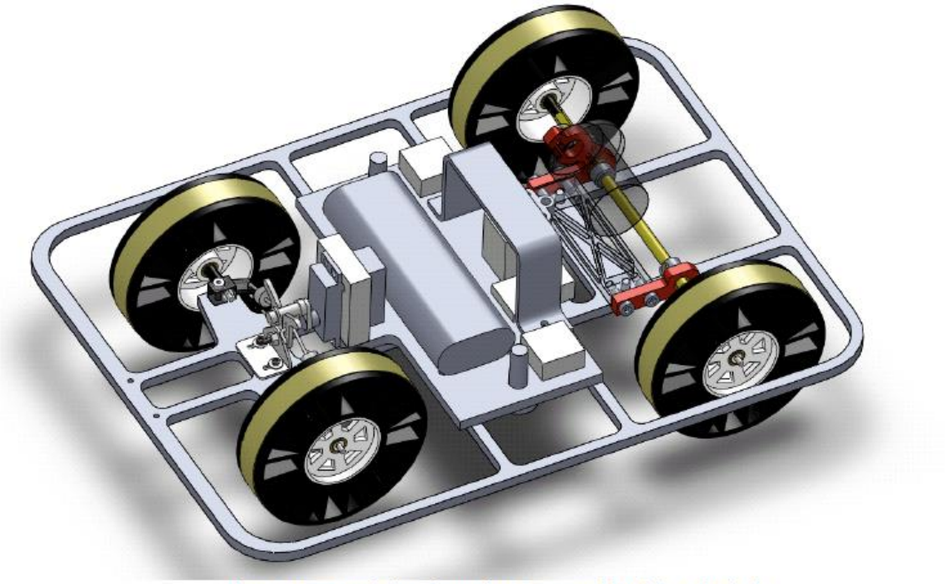
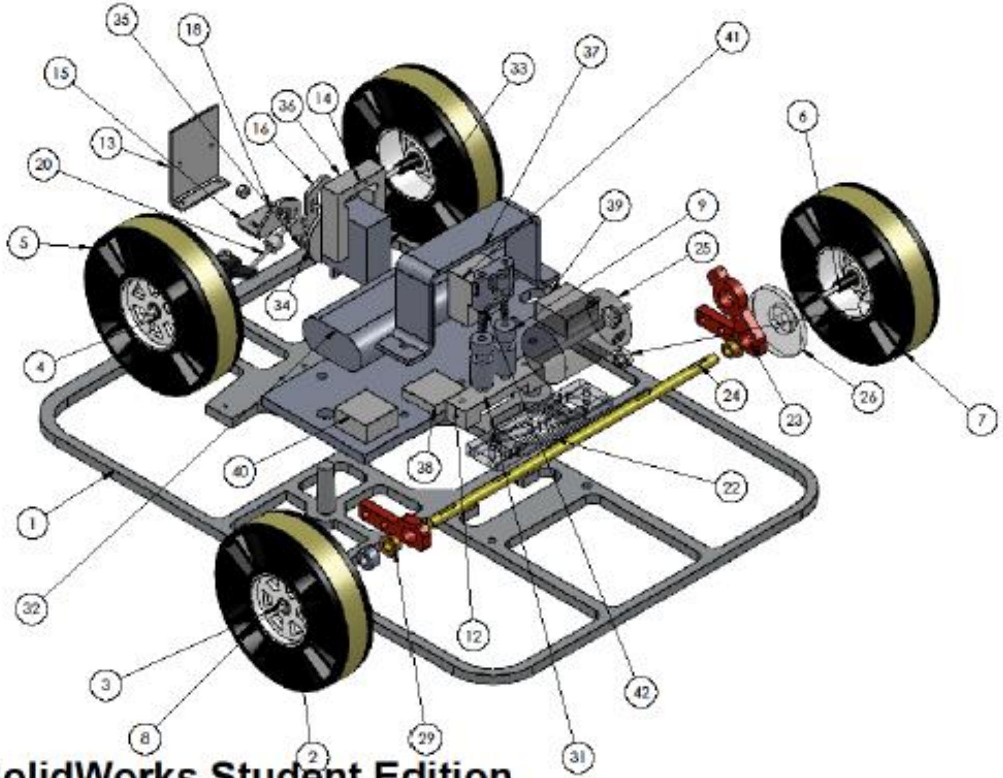


Figure 7- CAD rendering of complete car assembly without the body.

Detailed Prints

Exploded Assembly with BOM

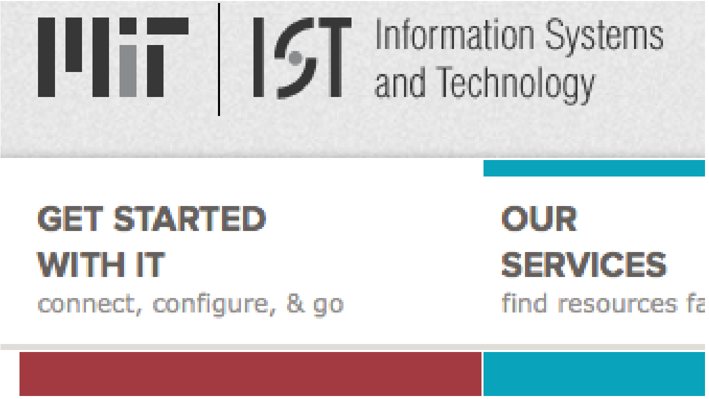
Assembly Exploded View



ITEM NO.	PART NUMBER	QTY.
1	chassis	1
2	wheel	4
3	frontaxle	4
4	bearing	8
5	front tire	4
6	SPACER	4
7	rubber band	4
8	nylon washer_small	4
9	Banana Jack	2
10	Maglock Catch	1
11	Maglock Strike	1
12	clip holder plate	1
13	Body Mount Bracket	1
14	steering block	2
15	steering mount	1
16	V bar	1
17	shoulder screw	2
18	screw 0_5	1
19	nut 4_40	1
20	tie rod	1
21	tie rod 2	1
22	DRIVETRAIN CONNECTOR BLOCK	1
23	MOUNT R	1
24	REAR SHAFT	1
25	MOTOR	1
26	LARGE GEAR	1
27	SMALL GEAR	1
28	STOPPER_RING	1
29	REAR_BUSHING	2
30	MOUNT R	1
31	Control Box Body	1
32	battery	1
33	servo	1
34	servo connector	1
35	servo drive connector	1
36	servo holder	1
37	handle	1
38	transponder	1
39	motor controller	1
40	tranciever	1
41	plug adapter	1
42	BP1252091(DualBanana)	1

Figure 8- Exploded Assembly with BOM

CADCAM and CNC

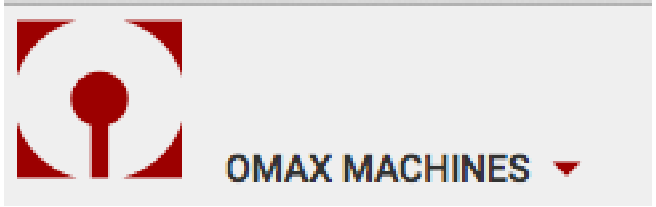


GET STARTED WITH IT
connect, configure, & go

OUR SERVICES
find resources fa

SolidWorks

Mastercam



OMAX® ABRASIVE WATERJETS

OMAX Instruction-
1st team meeting
Needs DXF file
OMAX app available

AUTODESK HSM

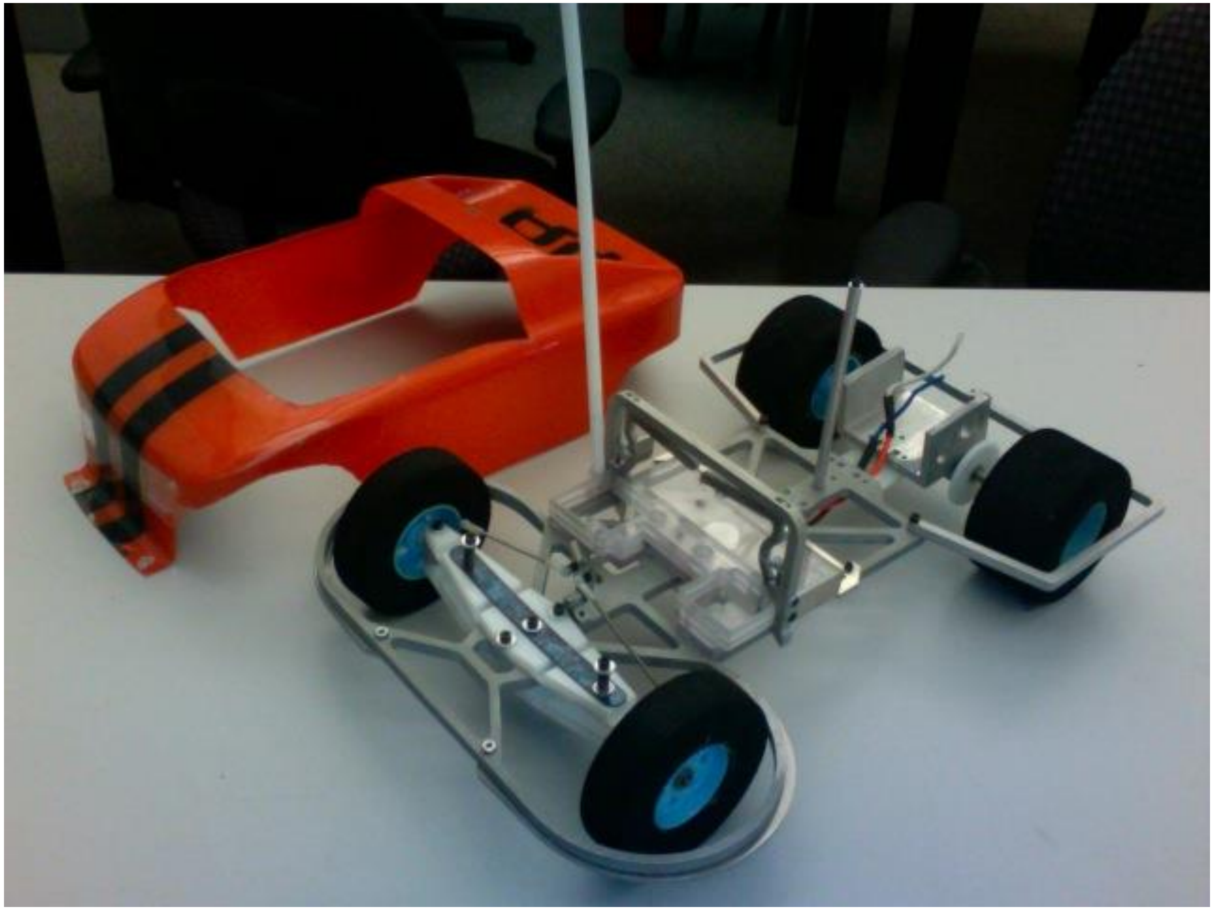
Check List

- Hand in information sheets
- Fill in Google doc for labs ASAP
- Attend Lab next week
- Read:

1. “Competitive Attributes…”
2. “Mfg. Processes and Control”
3. “Geometric Tolerancing”
4. skim Kalpakjian Ch 1-9.

- Homework #1

2.810 team project



http://www.youtube.com/watch?v=BcnwGV4tNNY