Automobile engine blocks, intricate though they are, cost a few tens of dollars apiece to machine; the automated factories that produce them are marvels of fixed automation. Raw materials enter one end of the line and hundreds of thousands of finished blocks stream out the other. The quantity is right for the auto industry and the price is right for the consumer. Unfortunately, this kind of fixed or "hard" automation is so inflexible that most of the factory itself has to be retooled to make a different engine.

Suppose that you need just one automobile engine block, not five hundred thousand. You take your thick sheaf of plans to a machine shop. Skilled machinists begin drilling, milling, and grinding formless metal into a shiny, eight-cylinder masterpiece of individual craftsmanship. Your bill could well be $2,500 instead of $25 to $50. So much for the mass production and one-of-a-kind production; how about the vast middle ground between these extremes?

A stark reality of American parts manufacture is that 50 to 75 percent of machined parts are made in batches of less than 200 in a given production run. The economic crux of the matter is that a businessman cannot really afford to build either a factory dedicated to manufacturing his 200 parts or to pay skilled machinists to make them one by one. For lack of available alternatives, he chooses the latter. He passes the cost on to his customers, who may respond by buying fewer parts or, even worse, buying the same part from foreign competitors who enjoy lower wage scales and/or more efficient—more flexible—methods of batch manufacturing. Flexible production technology is the key to the middle ground between mass- and single-product manufacturing.

Flexible automation means that machine tools can be programmed to carry out different operations on a variety of parts with minimum human supervision.

In a simple instance, a drill press might drill, tap, and ream holes of varying diameters and depths in a dozen different products moving through the factory on a single day, changing its own bits without expensive human help. This is just the kind of adaptability that is needed in batch manufacturing; it is just where American productivity may be lagging with respect to foreign competitors, according to a recent report of the General Accounting Office: Manufacturing Technology: A Changing Challenge to Improved Productivity.

American past successes in fixed automation and mass production were won through mechanical insight, trial-and-error, and just plain perseverance. It took decades and many blind alleys to adapt the concepts embodied in the first Model T line to modern plants spewing out hundreds of thousands of almost identical washers, TV sets and, of course, automobiles. There is no time for a similar experience-based learning process for manufacturing in batches of, say, 50 to 100,000 parts; flexible automation and parts manufacturing must be put on a rational scientific basis that can put it all together—the principles of metal cutting, the design of the tool, what happens when the tool contacts the workpiece, and the ability to instruct and control manufacturing operations. The tools, the cutting speeds, and the depths of cuts are all cookbookery. So is the strategy of selecting the machine tools and planning and carrying out the sequence of operations. The answer to cookbookery, invariably, is science.
Building a scientific base

Almost three decades ago, flexible automation became a realistic possibility when MIT engineers developed numerically controlled (NC) machine tools that received their instructions from punched tapes rather than flesh-and-blood operators. Then came ATC (Automatic Tool Changing) which conferred more versatility on NC, general-purpose machines. It was inevitable that computers would replace punched tapes and add their control capabilities to the machine tool in what is termed CNC (Computer Numerical Control) or DNC (Direct Numerical Control).

One of the first U.S. factories to synthesize these ideas in parts manufacture was the Ingersoll-Rand Company's Heavy Machining Center, at Roanoke, Virginia. This plant, designed by the Sunstrand Corporation, employs six NC machines and an automated parts transfer system operating under the control of an IBM 360/30 computer.

Castings to be machined into parts for Ingersoll-Rand products (chiefly hoists and winches) are attached to circular pallets that circulate around a racetrack-shaped transfer line. The computer selects parts from the racetrack and feeds them to the six machines, which can select from among more than 200 tools stored in their carousels. Machine operations include milling, turning, boring, tapping, and drilling. The six machines require only three operators plus a supervisor. The output matches that of 30 machines plus 30 operators in a conventional machine shop.

To the casual observer, Ingersoll-Rand's computer-controlled flexible manufacturing system, with its ingenious coordination of general-purpose tools and parts flow, might seem a nearly complete solution to the automation of batch manufacturing. The fact, however, is that, although the Ingersoll-Rand system does incorporate ingenious engineering and represents an advance in the state of the art, the whole operation is experience-based. It is thus of limited extensibility, rather than incorporating a generalizable, widely applicable base of scientific understanding. In retrospect, this is not surprising because no one has yet formulated the scientific principles of the batch manufacture of parts. Not even computers can lead us out of the Dark Ages, for they are also merely tools, not the new fundamental knowledge we desperately need.

The effort to put the batch manufacturing of parts on a scientific foundation consists of choosing a few research and development areas with high potential leverage—areas of ignorance where small investments may make large contributions to the country's expertise. Five of these areas, currently the focus of a National Science Foundation effort to come to grips with the batch manufacturing dilemma, include:

- The mathematical characterization of parts, assemblies, and manufacturing processes
- The strategy of batch manufacturing
- The rational design of injection molds
- Real-time measurement of the work piece
- Detection and measurement of tool wear

Automating the "front end"

Blueprints are the language of the conventional machine shop. Tons of them are needed to specify fully a ship or skyscraper. But a machinist poring over a blueprint, moving back and forth between it and his machine, is an incredible anachronism in our computerized age. The mechanical industries employ about 20 million people; between one-fourth and one-half of them are primarily information processors.

A research project at the University of Rochester is aimed at developing mathematical models of metal removal operations. This involves the mathematical representation of finished parts, raw
stock, and the machining operations necessary to convert stock to parts. The mathematical models underlie and are embodied in a computer language that will enable engineers (the parts conceivers) to "talk" more directly to machine tools (the parts makers). Ideally, an engineer could design a part with the aid of computer graphics and analysis programs and, upon specifying the materials to be used and other manufacturing parameters, have the computer generate a control tape for numerically controlled machine tools.

This, of course, is not automation in the sense of the Ingersoll-Rand plant. Rather, it is the automation of the immense amount of process planning and control that must be accomplished before a facility like Ingersoll-Rand's can begin cranking out parts. Thus, the University of Rochester work is directed toward automating the "front end" of batch manufacturing that deals with the description of parts, stock (raw materials), and the planning of manufacturing processes.

The "front end" is far more complex than it appears because the information being processed no longer consists of simple numbers. Computers crunch numbers with gluttonous ease because numbers (and many other factors) can be reduced to two-valued binary bits. A machine part, however, is a three-dimensional solid object. The objective is to reduce the geometrical description of the part to computer-digestible form. To compound the difficulties, the machine operations required to manufacture the machine parts are equally hard to reduce to a computer form. In addition, the two computer forms must be compatible. To date, no computer language exists for describing, mounting, and aligning on machines, drilling, grinding, shaping, turning, polishing, tapping, sawing, deforming, heat treating, and so on down a long list of machine shop operations.

A major accomplishment of the University of Rochester project has been a new approach to the systematic description of parts and their manufacture utilizing simple topological principles. In essence, mechanical objects are modeled as regular point sets in Euclidean threespace. Manufacturing operations that remove material can then be modeled via set difference operations. This description system has been acronymed PADL (Part and Assembly Description Language).

The design of PADL was influenced by a survey of real parts manufactured by the Gleason Works and The Xerox Corporation, both of which cooperate in the Rochester work. The surveys indicated that most simple—nonsculptured—parts can be described as combinations of prismatic and cylindrical solids: additions and subtractions of these simple solids.

The Rochester approach transcends the simple single part. Any refrigerator, bulldozer, bicycle, machine tool, or copier is an assemblage of parts, which are incorporated in subassemblies and assemblies. A subassembly is in effect a "super-part." The ultimate goal of the Rochester project, which lies at least a decade away, is the hierarchical description of the entire manufacturing process from raw material to subassembly to assembly to the finished product. Obviously, one does not "add" parts like one adds numbers, but if a computer can command a drill to drill it can also command put-and-take and other assembly machines to insert, bolt, rivet, paint, and package for shipment to the warehouse.

Simulating lazy production lines

Bottlenecks can occur anywhere in the production process. Assuming the front end has been successfully automated, with computers feeding parts-making instructions to numerically controlled machines directly or through the medium of tapes, where else is productivity strangled? A serious bottleneck occurs just prior to the NC machines themselves.

An individual NC machine tool, if it is provided with sufficient parts to work on, is loaded and unloaded without delay, has all the necessary cutting tools and programs, and is well maintained,
can be running 80 percent and more of the time, and actually be cutting metal over 70 percent of the time. A conventional (non-NC) general-purpose machine tool can rarely exceed 30 percent cutting time, and often falls much below that.

These utilization numbers go down sharply when machines are arranged in a shop and depend upon one another for delivery of parts to be worked on. Under these conditions net cutting time of NC machines with automatic tool changers has been known to drop below 30 percent.

Automatic materials handling and common computer control, such as on the Ingersoll-Rand system, provide the theoretical ability to give each machine "individual attention." In practice, cutting times in excess of 50 percent of the total have been achieved.

Obviously, expensive NC machines are underutilized in this kind of batch production and the factory is operating inefficiently. There is no need to build faster NC machines until parts can be fed to the machines more efficiently. A research program at Purdue University is aimed at discovering why these production lines are so sluggish and just what sort of theoretical Geritol should be administered to the computer overseers.

Consider the endless array of options available to a computer controlling an automated line producing, say, 12 different parts, each in batches of various sizes and each requiring 50 different machining operations, not all of which can be done at random. How does the computer know where to begin and how to proceed so as to maximize the utilization of all machines? Should it mix batches or should it proceed in serial fashion? What does it do if one machine tool breaks down? The minicomputers controlling most factory production tasks cannot begin to tackle such complicated questions; they need guidelines from bigger computers.

The Purdue group has attacked the scheduling problem on two fronts: scheduling theory and computer simulation of the production line.

The overall objective of the work with scheduling theories—somewhat surprisingly—is not to find the best schedule but rather the poorest schedules, which are duly extirpated. The reason for this apparent digression is that scheduling theories simply cannot yet cope with the complexity of the batch production problem. There are far too many potential schedules for each one to be examined individually, even with the biggest computers. What scheduling theories can do is identify classes of "pretty good" schedules but they cannot pick the best. In effect, they winnow the wheat from the chaff.

It is ironic that, with computers everywhere, many of the best scheduling techniques are heuristic and rely upon hard-won rules of thumb. (A simplistic rule of thumb or operating strategy for an array of machines might be "First come, first served.") Companies that have found good heuristic scheduling rules keep them secret. Even the best of these theories can be only suboptimal—perhaps very much suboptimal; they could also be very close to ideal. No one knows which.

Purdue engineers surveyed many of these scheduling theories, including network types, queueing theories, and various heuristic approaches. They decided that the best use of these theories would be in eliminating the immense number of very bad schedules for any specific batch processing line. This, of course, provided nothing concrete for the computer-supervisor of the line to work with, but it did reduce greatly the territory to be searched for optimally by a second approach: simulation.
The Purdue group decided to analyze an actual operating line using simulation techniques, with an eye to suggesting improvements that could then be tried out in practice. Working with the Caterpillar Tractor Company, they simulated its Peoria facility where a nine-machine Sunstrand Omnicontrl Direct Numerical Control line was in operation, linked to a remotely located PDP 11/20 computer that controls everything on a real-time basis.

The basic idea behind simulation is "time compression"; that is, the time of each and every operation in the production line is measured and then a sequence of operations is run on the computer much faster than real time. A full day of production might be simulated in just a few seconds. Many different schedules can be tried at modest cost without disrupting the real production line. Of course, the range of schedules worth simulating was reduced beforehand by appealing to scheduling theories. The simulations, in turn, lead to additional heuristic insights that further compress the areas of suboptimal, but increasingly better, operations. The Purdue work has now reached the point where simulations can predict the consequences of altering the scheduling of the Caterpillar line.

An arcane science

Not all parts manufacturing problems involve the shaping of metal. Volume for volume, American industry uses more plastic than steel. More than 20 billion pounds of plastic are consumed annually in home appliances, automobiles, toys, packaging, and other goods. Plastics are cheap, lightweight, strong, and can be injection-molded to tolerances of half-a-thousandth of an inch. Why bother precision-machining metal parts for a product when an automated injection molding machine can spew out superior plastic parts at lower costs?

The question is not entirely rhetorical. The design of injection molds, it turns out, is as much a black art as is the rest of batch manufacturing. The typical injection molding machine consists of a piston or screw-type injection unit that forces molten plastic from a reservoir into a mold at high pressures. The mold itself may be room-sized for a refrigerator liner or fit on a table top for gasoline engine carburetors. For mass production work, the mold may be multiple; it may produce several parts each injection cycle. The hot, viscous plastic surges into the mold through one or more "gates" propelled by the piston's pressure. The piston withdraws, the plastic hardens, the mold opens, and—all too often—out drops an incomplete or otherwise flawed part. The mold has failed to fill completely, a persistent, bedeviling problem in mold design. The secrets of good mold design reside in the accumulated experience and intuition of the mold designer. Unfortunately for American industry, many of the most expensive molds are sought outside of the United States.

Perhaps more injection pressure or lower plastic viscosity will fill the mold better. The number of gates can be increased and relocated. The variables the engineer can play with are many and their interrelations imperfectly understood. There is no way to predict just what will happen with a new mold. Modifying mold design in attempts to get it working well costs money (a large mold can cost a quarter of a million dollars) and time (the Instamatic plastic film cartridge mold took six years to develop). The injection mold is just the kind of tool where the substitution of science for experience in design could have an important effect on American productivity relative to foreign competitors.

The proper filling of an injection mold is a problem in fluid flow. The variables are many and the geometry complex. Over the years, the designers of aircraft and industrial heat exchangers have faced similar problems. The classical approach is to build instrumented scale models and try to find out what really happens as the fluids swirl around airfoils, tubes, and orifices. A similar tack is being taken at Cornell University where researchers are checking out some numerical models being developed in parallel. The overall objective is the establishment of quantitative guidelines for mold design—not in terms of theoretical formulas (which are presently out of reach) but rather charts and tables such as one finds in engineering design handbooks.

In this effort, Cornell has established ties with four companies vitally interested in injection molding: Ford Motor Company, Xerox Corporation, Cincinnati Milacron Company, and General Electric Company. These organizations have practical expertise, large-scale molding equipment, and other resources that a university laboratory could not hope to accumulate.

To begin, the Cornell project took a simple, disk-shaped mold with a single gate at the center. Temperature and pressure sensors were installed at strategic locations. Data obtained during actual operation of the mold were then compared with predictions made from analytical simulation models established for disk geometry. By working back and forth between analytical model and actual experiment, the model can be improved to the point where it can forecast accurately what will happen under specified conditions. This, of course, is just what the mold designers want, but for much more complicated geometries. Such experiment-verified analytical techniques aggregate into the handbooks and computer programs that characterize rheological and fluid mechanical design. It is not science in the sense that all the basic physical laws involved are understood, but it is a rational approach in a field where, more often than not, mold designs were "lucky" or unlucky, and where one all but consulted astrologers to make them work.

Tool wear and machining precision

In the nonautomated machine shop, a machinist is close to his machine and the workpiece. He watches his tools carefully and replaces them when wear begins to interfere with the speed and quality of his work. He also measures the workpiece repeatedly while it is on the machine. Continuous human surveillance has its advantages in terms of part quality and real-time control of all aspects of the production process.

In present-day automated plants, the machines are pretty much on their own. When a tool wears beyond a certain point, the quality of production decreases. If a tool breaks, the part being machined may be ruined and, worse yet, the damaged or incomplete part may be fed into another machine and put it out of action. The downtime of an automated production line may be as much as 40 percent for tooling reasons. In batch production, where hundreds of different tools may be used in a single day, automatic sensors are needed to replace the experienced eye of the veteran machinist.

NSF has awarded a grant to MIT's Department of Mechanical Engineering to develop a practical way of monitoring
tool wear. Over a dozen such techniques have been studied during the past two decades. Some examples are optical scanning of the tool, analysis of tool-wear particles in the chips, the analysis of sound and vibration from the tool, and measurement of the cutting force required. The MIT approach involves the implementation of a small quantity of a radioisotope in the tool itself and the frequent measurement of tool radioactivity with a Geiger counter. As minute bits of the tool wear off, the radioactivity of the tool decreases. When it drops below a predetermined level, a warning system can be triggered, shutting the machine down and calling a human supervisor. Outright tool breakage would also shut the line down before damage can be propagated down the line. The MIT method is potentially very reliable, adaptable to different tools, and generates an electronic signal easily digested by monitoring computers.

Called the Micro-Isotope-Tool-Sensing method for obvious acronymal purposes, prototypes have employed the isotope silver-110m (silver-110 in a metastable state) in quantities less than 10^8 curie—a very safe level. Sparking techniques have been explored as methods of implanting the silver wear zone in the cutting of the tool. Present thinking calls for placing a tiny (0.001 inch in diameter) radioactive particle on the wear surface or in a shallow pit. After each cutting cycle (a "pass" on a lathe, for example), the whole tool is checked by the counter. The counting rate will drop to background levels when this tiny implanted particle has been worn away or if the tool breaks.

An automated tool-wear monitor "sees" only one variable out of several that a human machinist normally controls. Numerically controlled machine tools, for all their superhuman attributes, are driven by motors that move the tool a certain amount this way and a certain amount that way. The tool may move precisely as specified by the program but the finished part may not meet specifications. Tool wear is only one reason. Others include:

- Backlash in the machine's gears and lead screws
- Deflection of the tool under the applied load
- Thermal expansion of the part being machined

Some progress has been made in eliminating these sources of error by adding transducers to various parts of the machine, but in almost all cases a secondary parameter is measured rather than the dimensions of the part being machined. The automation industry needs a good, real-time substitute for the conventional hand-held calipers and micrometers.

A group at Case Western Reserve has tackled this problem optically. When one considers how one might measure a part remotely to within a few ten thousandths of an inch without removing the workpiece or interrupting the machining operations, optical methods quickly come to the fore. Interferometers seem made to order but they usually require a specular (polished) surface and actually give only relative measurements. However, nonspecular reflectors of dual laser beams provide the opportunity for precision triangulation—a sort of "microtransit." In the Case Western concept, the beam from a laser is split and the two resulting beams are modulated at different frequencies. The two spots of light are kept superimposed on the workpiece by a system of lenses and a photodetector, which drive a servo system. As the machine tool cuts away at the part surface, the superimposed spots tend to diverge as the distance to the part surface changes. The servo system drives a precision lead screw that separates the split-beam source by just the amount needed to bring the two spots back into superposition. Knowing all the angles in the instrument, the change in dimension of the part being machined can be calculated from the distance the lead screw moved the laser sources.

Engineers at Case Western Reserve have built a prototype using a helium-neon laser. Lab tests suggest that an operating system on a real machine tool should be able to measure part dimensions to within 0.0002 inch. With direct part measurements of this accuracy plus a tool wear/breakage monitor, automation is replacing to a considerable degree human eyes and the hand-wielded micrometer.

**From archipelago to continent**

The automation projects described above can be viewed as islands in a fairly deserted ocean. Other projects are under way, such as a challenging attempt at Purdue to quantize parts attributes (holes, for example) and machine tool operations (say, drilling) in computer-digestible descriptors. These so-called "unit machining operations" represent one more attempt to reduce manufacturing know-how to a mathematical science—a stable continent upon which one can base reliable predictions.

Reliable prediction, after all, is the major hope that science offers any field of knowledge. Chemistry in its formative days resembled the current state of development of knowledge of manufacturing technology. By building a mechanical equivalent of chemistry's Periodic Table, finding and measuring the tool designer's concomitant of the chemist's pH, and so on, manufacturing (probably no more complex than chemistry) can be systematized, too. Of all industries, the chemical industry has been automated most successfully. It is a good historical precedent to follow.

Research discussed in this and in the preceding article ("Automating the Assembly Line") is supported by the Production Research and Technology Program of the National Science Foundation.