dition, optical beams do not interfer with each other and can cross each other without interaction.

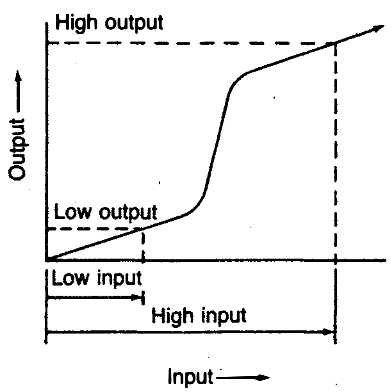
Although these attributes have been exploited in analog optical devices, they have not yet been fully applied to digital systems. The main reason for this has been the lack of suitable optical logic and memory devices, but this situation has recently changed.

Transphasors: The fundamental components of any digital logic or memory device are switches capable of two different states of transmission. A dominant factor in the speed of the component is the time required for a switch to change states. Currently, computers use transistors to perform the switching function. The fastest these devices can be made to change states is about a nanosecond, or a billionth of a second.

Researchers at several laboratories (for example, Bell Labs in the United States and Heriot-Watt University in Scotland), however, have developed an experimental optical device analogous to the transistor. This is called a transphasor, and it can achieve switching times on the order of a few picoseconds (a picosecond is a thousandth of a nanosecond).

Like any switch, the transphasor is based on a physical phenomenon whose input-output relationship takes the general form of the characteristic curve shown in **Figure 2**. The curve's nonlinearity is the key attribute that produces a binary (that is, high versus low) output based on a binary input and permits the implementation of logical functions.

FIGURE 2
Characteristic nonlinear curve of binary switch



For example, if we desire a device that outputs a high signal only if its two inputs are simultaneously high (the classic *AND* function), we can scale the inputs such that only when they are both high will the total input signal exceed the kink in the curve of Figure 2 and produce a high output.

Similarly, if we desire a high output when either one of the two inputs is high (the *OR* function), we can scale the inputs such that a single high input exceeds the kink in the characteristic curve and produces a high output. Given the *AND* and *OR* functions, all of the logical functions required of binary digital computers can be constructed.

Most transphasors are constructed using a Fabry-Perot interferometer and a material with a nonlinear refractive index in the interferometer cavity. In its simplest form, the Fabry-Perot interferometer consists of two plane, partially reflecting mirrors placed parallel to each other and separated by a cavity or space. If a coherent beam of light is input through one of the mirrors, the intensity of the beam output from the other mirror is dependent on the interference pattern set up in the cavity by the incident and reflected beams.

At full destructive interference, the intensity in the cavity is almost zero and transmission through the output mirror is negligible. However, at full constructive interference, the intensity of the cavity can be as much as 10 times the intensity of the incident beam. Because of the losses through the output mirror, the intensity of the output beam is roughly equal to the incident beam intensity for this situation. By placing a material in the cavity whose refractive index (ratio of speed of light in a vacuum to its speed in the material) is dependent on the intensity of the light passing through it, the conditions under which constructive or destructive interference take place can be made dependent on the intensity of the incident beam.

For example, suppose, at low incident beam intensities, destructive interference prevails in the cavity. The intensity of the output beam is therefore negligible. As the intensity of the incident beam is increased, it causes the material in the cavity to achieve a refractive index that results in constructive interference, and the intensity of the output beam increases

Analog computers will transform computation

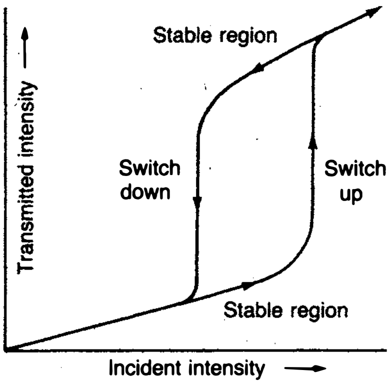
Digital computers are incapable of truly representing any process in nature, from the propagation of sound to the growth of an economy. The reason for this is that they internally represent all data or information with discrete, linear objects: integers (that is, the numbers, 1, 2, 3, . . .) in the form of binary numbers (ones and zeros). The concept of an **analog computer** is based on the idea of representing the "data" of nature, in forms close to those in which they occur in nature. Digital computers are unable to directly represent rotational action, exponential functions, and even square roots. It is not unrelated that the principal use of computers today is in the limited domain of accounting.

Pythagoras showed over 2,000 years ago that it was impossible to represent the square root of two with either a single ratio of integers (that is, a so-called rational number), or a finite sequence of them. Archimedes showed some hundreds of years later that it was impossible to dramatically. The resulting input-output relationship looks generally like that shown in Figure 2.

By altering the length of the interferometer, the wavelength of the incident beam, or the material in the cavity, a hysteresis loop can be created, as shown in **Figure 3**. In simplified form, the occurrence of a hysteresis can be explained as follows: As the intensity of the incident beam is reduced, enough light remains in the cavity to keep the refractive index near the value corresponding to constructive interference. Thus the "decreasing incident intensity" curve is to the left of the "increasing incident intensity" curve.

FIGURE 3

Characteristic curve with hysteresis, or bi-stability



An optical device that exhibits this behavior is said to be optically bistable because it has two stable regions where the transmitted intensity changes very little with variations in the incident intensity. Either the high state or low state can be maintained indefinitely with an incident beam of intermediate intensity. The obvious application of such a device is as a binary memory element.

The transphasor described above is known as an intrinsic system because its performance is based on the intrinsic refractive properties of the material in the interferometer cavity.

Hybrid systems: Work is also being done on so-called hybrid systems, which typically employ a crystal whose refractive index depends on an applied voltage rather than incident light. The voltage is generated by a light detector that detects a portion of the output beam of the interferometer via a beamsplitter. The resulting feedback loop causes the electro-optic crystal to behave in the same manner as a crystal with an intrinsic nonlinear refractive index. Depending on the tuning of the feedback loop, a characteristic curve of the form shown in Figures 2 or 3 can be produced.

Transphasors have also been constructed without the use of Fabry-Perot interferometers. Most of these hybrid devices are based on liquid crystal light valves. This device is a small wafer sandwich essentially composed of two different mate-

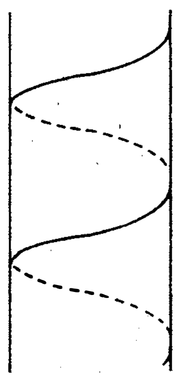
represent a circle (and therefore, rotational action), with such a finite number sequence, in the form of a multiple-sided polygon. Later geometers showed that *e*, a characteristic of the logarithmic spiral (as π is a characteristic of the circle), is also unmeasurable using sequences of rational numbers.

The point of changing over to the use of analog computers, is not to find a different, "more efficient" way to produce digital representations, but to dispense with digital representation altogether. Analog (i.e., nonlinear) representations are primary. When the need arises to convert an analog representation into a digital form, this is trivially accomplished.

The first attempts to construct analog devices used the waveforms of the low-frequency electromagnetic radiation known as electric current, to directly represent the nonlinear "arbitrary functions" or data, characteristic of all natural processes. Our increasing mastery of coherent light and optics, enables a more direct path to the analog computer, unhampered by the limitations of electrical circuitry.

The figure shows the approximate form of coherent laser light, under consideration as the building block of optical computers. The superiority of this form of data representation over the digital, is obvious. First, nonlinearities, such as rotational action, are the form of the representation itself. Progressive frequency upshifting enables the direct representation of the logarithmic spiral. Second, light is primarily a hydrodynamic phenomenon. As such, it will provide a way to represent hydrodynamic differentiation (e.g., solitons or shock waves).

This direct representation of nonlinearities in nature will result in analog computers which can solve several nonlinear problems in a timeframe in which a digital machine would have just gotten started. In short, the introduction of optical analog computers based on these principles, opens up a whole new domain of possibilities.



The simplest form of circular action: the cylindrical helix.