Far left: William Hansen (right) and colleagues with a section of his first linear electron accelerator, which operated at Stanford University in 1947. Eventually 3.6 m long, it could accelerate electrons to an energy of 6 MeV. (Courtesy Stanford University)

Left: Ernest Lawrence's first successful cyclotron, built in 1930. It was 13 cm in diameter and accelerated protons to 80 keV. (Courtesy Lawrence Berkeley National Laboratory)

When discussing the relative merits of electron and proton colliders, the background situation is complex because the factors that cause them are quite different. When accelerated, and especially when their path is bent by magnets, electrons radiate X rays in the form of synchrotron radiation. Protons usually have more serious interactions with residual gas atoms, and those that deviate from the nominal collider orbit are more apt to produce unwanted backgrounds from such causes.

A much more difficult—and to some extent controversial—subject is the comparison of the complexities of events initiated by electrons with those induced by hadrons in general, and protons in particular. Today particle physicists are usually, but not always, interested in the results of "hard" collisions between the elementary constituents (by which I mean entities considered to be pointlike at the smallest observable distances). Because protons are composite objects, a single hard collision between their basic constituents will be accompanied by a much larger number of extraneous "soft" collisions than is the case for electrons. Thus the fraction of interesting events produced in an electron machine is generally much larger than it is for proton machines. So the analysis load in isolating the "needle" from the "haystack" tends to be considerably more severe at hadron machines.

Beyond this problem is the matter of interpretability. When we use electrons to bombard hadron targets, be they stationary or contained in an opposing beam, we are exploring a complex structure with an (as-yet) elementary object whose behavior is well understood. Thus the information about the structure of the proton resulting from electron-proton collisions, for example, tends to be easier to interpret than the results from proton-proton collisions. All the above observations are generalities, of course, and there are numerous and important exceptions. For instance, if neutrinos or muons—copiously produced as secondary beams from proton machines—are used to explore the structure of hadrons, the results are complementary to those produced by electron beams.

Everything I have said about electrons is also true of muons. The use of muon beams offers significant advantages and disadvantages relative to electrons. The two lightest charged leptons, the electron and muon, experience essentially the same interactions. But muons, being heavier, radiate far less electromagnetic energy than do electrons of equal energy; therefore backgrounds from radiative effects are much lower. On the other hand, muons have a short lifetime (about 2 microseconds), whereas electrons are stable. Colliding-beam devices using muons must be designed to be compatible with this fact. In addition, the remnants of the muons that decay during acceleration and storage constitute a severe background. Thus, while the idea of muon colliders as tools for particle physics has recently looked promising, there is no example as yet of a successful muon collider.

BUT THERE is an overarching issue of costs that dominates the answer to the question, "How large can accelerators and colliders become, and what energy can they attain?" The relationship of size and cost to energy is determined by a set of relations known as scaling laws. Accelerators and colliders can be broadly classified into linear and circular (or nearly circular) machines. With classical electrostatic accelerators and proton or electron radiofrequency linear accelerators, the scaling laws imply that the costs and other resources required should grow about linearly with energy. Although roughly true, linear scaling laws tend to become invalid as the machines approach various physical limits. The old electrostatic machines became too difficult and expensive to construct when electrical breakdown made it hard to devise accelerating columns able to withstand the necessary high voltages. And radiofrequency linear accelerators indeed obey linear scaling laws as long as there are no limits associated with their required luminosity.

The scaling laws for circular machines are more complex. Ernest