Digital vs. Analog; Linear vs. Switching

• In systems, one encounters the terms "digital" and "analog." In solid state devices, or semiconductors, one encounters the terms "linear" and "switching." After you've studied applications for a bit, you conclude that digital systems use switching-type semiconductors, while analog systems use linear-type semiconductors. In general, that is quite right, but as you have probably gathered by its being selected as a subject for this column, it is not quite as simple as that!

Digital vs. analog can be illustrated quite well by a couple of commonplace examples. To tell time, you can have digital or analog clocks or watches. To calculate, you may use a digital or analog calculator. In case you are not familiar with those terms, even in that context, a digital clock or watch is one that tells you the time with numbers, such as 3:15. After being at 3:15 for precisely 60 seconds, the numbers will change to 3:16.

On the other hand, an analog clock uses hands that move over a circular face, practically continuously. During the 60 seconds between 3:15 and 3:16, the minute hand would slowly move from one position to the other, continuously, if imperceptibly.

DIGITAL CALCULATOR VS. SLIDE RULE

A digital calculator is virtually the only kind in use today. But some of us remember when an engineer was identified by that thing called a sliderule, invariably sticking out of his pocket, as his badge of office. Ask an engineer a question—virtually any question, in those days—and he'd pull out the sliderule, much as anyone else looks at a watch or clock to tell the time.

Like the digital timepiece, the digital calculator gives a readout, in numbers. It can be programmed to a variety of ways of reading out, but they all use discrete numbers. The sliderule, on the other hand, like the old-fashioned timepiece, has numbers on it, but you do not exactly read the numbers; instead you interpolate what the hands tell you, by their position with respect to the numbers. You interpolate a sliderule in much the same way. The sliderule was an analog calculator.

What has that to do with audio? Well, put simply, for years audio had to be analog: an audio waveform was amplified, and processed in other ways, based on either maintaining, or changing, its shape as an analog of the sound it represented. Sound could be synthesized, by putting frequencies together, but what you put together, in those days, were waveforms, so it was still analog.

DIGITAL TECHNIQUES

Nowadays we are getting into digital techniques with audio. This is like running a high-speed computer over the waveform, and having some kind of memory remember, or program, the rate at which the numbers change, and process the waveform, in terms of its numbers, rather than its analog shape. Doesn't that seem awfully more complicated than the simpler linear amplifiers and other audio devices of earlier times?

More complicated, maybe, but look what has happened to calculators and time-keeping. The calculator or the digital watch must contain the equivalent of hundreds, probably thousands of individual transistors which, in earlier times, would have cost the earth. But modern technology has changed all that, by use of integrated circuits—i.c. chips—that really cut cost. The fact that you can get a digital watch, for $19.95 that is a better timekeeper than one of the old analogs costing many times that much, shows what we have gained: precision.

The same with calculators. A precision sliderule was costly—far more costly than a digital calculator that can actually outperform the sliderule by a long way, in every way. That is why engineers don't use sliderules any more. There is much the same to gain in audio, once we learn how to use it.

Of course, there are linear and digital i.c.s, just as there are linear and digital transistors. Only in individual transistors, those used for digital work are usually called "switching" types. This is because they are intended to be used in two-state mode, between which states they switch. Which brings us to the question: What really is the difference between a linear semiconductor and a switching semiconductor?

When you get into i.c.s, of course, the

circuit configuration makes the difference: the transistors and other semiconductors of which it is composed, are arranged in one of two ways. Either so the individual transistors switch from one state to the other, and cannot be held at any intermediate condition, such as a "flip-flop" circuit; or else so that they do operate over a continuous range of variation, like an amplifier.

But the individual transistors and diode that go into such a package, although they are produced by a process that puts hundreds or thousands of them together on a tiny chip, have characteristics that render them more suitable for either linear or switching operation. If you're buying an i.c. chip, you don't have to bother about it, because the chip designer took care of that. But as soon as you get off of integrated circuits, into what is known as discrete components—meaning you are now dealing with individual transistors and other circuit elements, not with complete chips, you need to know what it's all about.

LINEAR OPERATION

Applied to any semiconductor, the word "linear" is really a misnomer. A resistor can be linear, but a semiconductor cannot: it conducts one way, does not the other. But the relationship between "how much" it conducts, and the control, be it voltage or current, that determines that "how much," can be more or less linear, *over a certain range*.

Anything that goes from nonconduction to conduction, does so in non-linear fashion, with a sort of curve: square-law, exponential, or something. But if that conduction is controlled in a way that produces amplification, such as the base current controlling collector current in a grounded emitter stage, there is usually another kind of curvature, coming into the picture: beyond a certain base current, there will be no further increase in collector current.

By properly selecting values in the circuits associated, the relationship between collector current, and the base current that controls it, can be quite close to linear, between certain limits. This means that, between those limits, every microamp change in base current will be accompanied by, say 200 microamps change in collector current.

But at one place a change of 1 microamp base current may produce a change in collector current of 180 microamps, while at another place, it would be 220 microamps. That is non-linearity and must be corrected by use of negative feedback. In theory, a linear transistor has been designed so that, by using the proper circuit values in association with it, it is close to linear, so that feedback will make it close to perfect.

Data about a transistor designed and produced for that kind of application, will tell you how good it is, what values to use, so you can build a circuit round it that makes it as linear as you may want.

SWITCHING OPERATION

A switching transistor, on the other hand, is intended to be operated between two extreme states: fully conducting, or completely non-conducting. This does not mean it does not have in-between states, but that it spends as little time as possible there. If it fully conducts at 1 amp, then when it is switched on, current changes from zero to 1 amp. There is an instant in time when it is half an amp, or any other intermediate value.

But the circuit is arranged to expedite the change, so it spends as little time as possible in between. That is called switching speed. And a switching transistor is designed to give the maximum switching speed, not to switch with great linearity. But there is no magic that makes one transistor work as a switch, and another as a linear amplifier. What makes that difference, is the circuit you build around it. And of course, if the transistor comes as a tiny part of an i.c. chip, that is already built around it, you don't have that option.

Whether a semiconductor works as a linear or switching device, it takes time to change its state: the response of the controlled current, to the controlling current, is not instantaneous. When base current changes, collector current changes a little later, perhaps only a microsecond or less—time measured in nanoseconds perhaps—but it does take time.

In the linear mode, this time relates to the high-frequency roll-off of the system. The faster the changes occur, there comes a point where the semiconductor ceases to follow them completely, because they are too fast. In the switching mode, such time limits the switching capability: how many times a second, or whatever units you use for measuring time, it can perform such a switching action.

And if you are using switching circuits for digital audio, that of course relates to frequency roll-off again, but in a slightly different way. Where the linear mode gradually fails to follow, the switching mode reaches a point, where the behavior becomes erratic.

A LITTLE OF EACH

Now, is a synthesizer, or an electronic organ, digital or analog, linear or switching in the circuitry it uses? Today, few of them are either completely one or the other, but a mix of each. The earliest oscillators, used to generate audio frequencies, used positive feedback that was frequency selective: the frequency selection could use either L-C circuits, or a system of R-C circuits. Either way, just one frequency got fed back, so an oscillation built up at that frequency. They are little used today, because the exact frequency depended on so many factors that tuning became quite involved.

A frequency counter is a digital device. In earlier electronic organs, frequency counters, or dividers, produced successive octaves down the scale, for each of 12 master frequencies that produced the top octave of notes. But today, much more sophisticated counters are available. Starting with a few megahertz, as the master frequency, different counters can count off quite high numbers, to produce all the top octave of semitones, properly spaced, by a built-in count programming. That is digital. Then lower octaves can be obtained from that top set, as before.

An advantage of this method is that the whole organ can be tuned by adjusting the frequency of one master oscillator. A control available to the organist enables him to tune his instrument into unison with an orchestra, a piano, or whatever, almost instantaneously. Only the digital technique makes that possible. But from there on, a wide variety of techniques can be brought to play, in producing timbre, waveform variations, and so forth. Some are digital, some are analog, and some a mixture of each.

It's a challenge, this new world of audio. But when wasn't it? How do you think we got to where we are? ■