Electronic circuits inevitably involve reactive elements, in some cases intentionally but always at least as parasitic elements. Although their influence on circuit performance may be subordinate for a particular circuit reactive elements introduce an ultimate limitation on frequency response/switching speed. Energy storage in reactive elements introduces consideration ‘past history’ into the analysis of a circuit.

This note examines switching delays associated with circuit capacitance and inductance. There are related delays associated with device internal phenomena, generally significant only for very fast changes. These device-specific contributions are considered elsewhere; ordinarily they are of little import other than for significant time intervals less than (roughly) 10 to 100 nanoseconds. Switching is examined here in the context of a bipolar junction transistor circuit.

**Switching a Capacitative Load**

The circuit on the right is a simplified CE amplifier with an external capacitor load; the capacitor may represent an inevitable circuit parasitic or it might approximate the capacitance that would be added by an additional stage of amplification. A voltage pulse is applied, increasing the base input voltage from an initial zero level for which the transistor is cut-off, to a level at which the emitter junction is turned ON. The junction becomes cut-off again on the trailing edge of the pulse. The pulse width is assumed to be wide enough so that turn-on and turn-off transients are disjoint. The basic question considered is the locus of the operating point on the IC-VCE plane.

**Qualitative Evaluation**

Consider the circuit performance qualitatively at first; this is done with reference to the figure to the right. A representative constant base-current characteristic is shown, and superimposed on the graph is the load line for the circuit. Initially (base voltage zero) the transistor is cut-off and there is no collector current; the collector voltage then is VCC. This is the abscissa point labeled 'cutoff' on the figure, and is the quiescent point so long as no base voltage is applied. Note particularly that energy is stored in the capacitor, i.e., the capacitor is charged so that the voltage across it is VCC.

Now suppose an abrupt base voltage change occurs corresponding to the leading edge of the base voltage pulse. (As a practical matter ‘abrupt’ means the change occurs within a time interval much shorter that that within which the circuit can respond; the analysis will indicate how small this interval need be.) Base current rises abruptly to a finite value, approximately equal to (pulse-height - 0.7 volt)/ RB. The collector voltage however remains at VCC initially, since the capacitor charge cannot change instantaneously. Hence the operating point jumps abruptly, as shown, to the collector characteristic corresponding to the base current. Note that the transistor is not saturated initially whatever the base current because the collector voltage is constrained by the capacitor. Note also that initially there is no current through and so no voltage drop across the collector resistor. It is the capacitor that supplies the BJT collector current (so that to the extent that the collector current remains constant the collector voltage drops linearly).

As the capacitor discharges, lowering the collector voltage, current through the collector resistor increases and current from the capacitor decreases. Roughly equal magnitudes of change are involved, at least to the extent that the transistor collector current for a fixed base current remains constant. As the collector voltage decreases the operating point moves down the constant base current characteristic until the intersection with the load line is reached. At this point the collector current is provided entirely through the collector resistor. There is no current drawn from the capacitor, and so no further decrease in collector voltage.
This is the steady-state condition that persists until the amplitude of the base-voltage pulse changes. The transistor may or may not be saturated in steady state; this depends on the circuit element values fixing the intersection of the load line and the collector characteristic. In general the turn-on will be fairly rapid, because the transistor provides a relatively high-current discharge path for the capacitor.

Assume now the steady state has been reached, and then after that the base voltage is brought back to zero voltage, once again cutting off the transistor; this is at the trailing edge of the base pulse. The collector current drops immediately (ideally) to zero. However the capacitor again does not permit the collector voltage to change abruptly. Hence the operating point drops abruptly to intersect the axis; zero current, same voltage. Current now flows through the collector resistor to charge the capacitor, and the operating point moves along the abscissa to return to steady state at $V_{CC}$.

**Quantitative Evaluation**

A PSpice analysis of the switching circuit considered was performed, using the 2N3904 PSpice model and circuit element values as shown to the left. The computed currents as a function of time are shown in the figure below. The transistor collector current (which should be distinguished from the current provided by the power supply) jumps immediately on turn-on to a magnitude determined by the collector characteristic corresponding to the base current; the transistor is not saturated at this point and there is no current-limiting because of saturation. A turn-on current spike of this sort (see plot below) can cause damage if the current is not limited to a safe value by one means or another. In this example that the base resistor provides limiting, but the point really is that the matter should not be left to chance.

The supply current, on the other hand, initially is zero; the capacitor holds the voltage drop across the collector resistor to zero. As the supply current increases (the capacitor is discharging through the transistor and consequently the collector voltage is decaying) the collector current decreases in this illustration. As is not uncommon in such switching the base current magnitude used generally is intended to saturate the transistor. Because the capacitor at first prevents the transistor from saturating an initially larger current speeds the capacitor discharge.

Eventually steady state is reached; there is no current contributed by the capacitor, and the power supply provides the collector current. When the transistor is cutoff on the trailing edge of the base voltage pulse the collector current drops to zero immediately. The supply current, however, continues to flow, recharging the capacitor. A plot of the computed collector and power supply current is shown below.
Switching an Inductive Load

Because of a fundamental conflict between the physical laws associated with the inductive effect and the practical and economic constraints of monolithic construction the phrase integrated circuit inductor is by and large an oxymoron. On the other hand discrete inductors are important in a number of applications; high-current mechanical relay switches are a specific example. A simplified transistor-actuated switch circuit is shown to the left; the dotted rectangle represents a relay coil having a winding resistance $R_L$ and an inductance $L$; associated mechanical switch contacts are not shown explicitly since they are not involved in the present discussion.

As was done in the capacitor switching illustration a pulse is applied which temporarily switches the transistor from a cutoff state to a conducting state. Also, as in that earlier illustration, we first examine the circuit behavior during the pulse qualitatively.

Qualitative Evaluation

The inductance is a more sinister circuit element than a capacitor in the sense that it stores energy dynamically, i.e., via a current flow through the inductor. For capacitor loading turning off a power supply is a relatively benign operation, although there are some hazards. Capacitors discharge their stored energy if there is a current path, but if not they remain effectively dormant in an energized state. An inductor, on the other hand, stores its energy in a current flow, and in general turning off the power supply means turning off current flow. An inductor responds to a changing current by generating a voltage which attempts to mitigate the change; the faster the change the larger the generated voltage magnitude. Unfortunately the typical result, particularly where care is not taken, is to produce a destructive release of the stored energy.

A sketch of a representative pulse trajectory on the $I_C$-$V_{CE}$ plane is drawn below. Initially the transistor is cutoff and the operating point is at ($V_{CC}$, 0). When the base drive turns the transistor ON the operating point must lie on the transistor characteristic that corresponds to the base current applied. On the other hand the inductance prevents the collector current from changing immediately. To accommodate both requirements concurrently the collector voltage drops immediately and moves to the zero-current intersection of the collector characteristic; the collector voltage change involved is induced by the inductive reaction to an attempt to change the current. Note however that the
current is in the process of increasing. As the current increases operation moves up the saturation part of the collector characteristic and over until the load line is intersected.

This corresponds to the steady-state operating point. In most instances the operating point will be selected to saturate the transistor so that the collector dissipation will be relatively small.

**Quantitative Evaluation**

A PSpice computation of the turn-on transient follows first. The turn-off process (which involves the diode branch) is considered separately. During turn-on the diode is reverse-biased and so this branch is inactive and can be ignored.

The computed turn-on transient response is shown in the figure following below (input step starts at 10µs). Note that the collector current remains zero initially and then rises approximately exponentially (along the collector characteristic) into steady state (with a small overshoot). Similarly the collector voltage initially drops rapidly towards zero (through saturation), and remains low as the current rises (along the saturation portion of the collector characteristic). As the operating point moves to the intersection of the load line and the collector characteristic the voltage and current increase to their steady-state values.

The IC-VCE locus for the turn-on transient is plotted below.
A similar calculation can be made for the turn-off transient but this is not done here. The reason is absent protective measures circuit operation is quite erratic and in practice generally destructive. On the trailing edge of the base pulse the transistor is suddenly cut-off. However the energy stored in the inductor cannot simply disappear (conservation of energy), i.e., the current through the inductor cannot immediately drop to zero. The faster the current attempts to decrease the higher the inductive voltage generated \( V = L \frac{dI}{dt} \). The inductive increase in collector voltage tends to increase the collector current (because of the Early effect). Unfortunately even a relatively modest rate of change of current causes a very large induced voltage, usually increasing the reverse bias of the collector junction beyond the point where junction reverse breakdown occurs. This new current flow mechanism leads into unstable operation with the usual consequence being destruction of the transistor. We do not consider this operation further. However we do consider one modification of the circuit to avoid this problem.

Actually the general nature of a solution is fairly straightforward; simply provide a current path to replace conduction through the transistor which enables the stored inductive energy to be dissipated harmlessly. This added current path should be activated only when the transistor is turned off, since energy is supposed to be stored when the transistor is turned ON.

One method to accomplish the objective is to add a resistor and diode as shown above. When the transistor is turned ON the diode blocks current flow through the added branch and the turn-on operation is as described before. On turn-off however the inductive voltage generated increases the collector voltage to the point where the diode is turned ON and what was collector current now flows through \( R \). Note that if the steady-state collector current is \( I \) then the collector voltage jumps by an amount \( IR \) + diode drop and thereafter decays exponentially with time constant \( L/(R+R_L) \). The amount of the initial voltage jump can be limited by the choice of \( R \), but there is a trade-off between rapid decay (\( L/R \) small) and a limited voltage jump (\( IR \) small).

The figure below is a sketch illustrating the IC-VCE turn-off transient. On turn-off the collector current drops rapidly the base drive is removed. However the inductor current is diverted through the diode branch, which is turned on by the inductive voltage generated. The collector voltage rise is limited to a value sufficient to maintain (initially) the current that was carried by the collector.