‘Bootstrap’ Ramp Generator

For many purposes, for example providing a time axis for oscilloscope displays, a voltage varying linearly with time is needed. In many instances a satisfactory approximation to such a ‘ramp’ is obtained by making use of a simple RC charging circuit, using just the initial part of the exponential charging response. For a time interval small compared to the RC time constant the exponential is well approximated by a tangent at the origin. Modifications of this basic procedure improve in one way or another the linearity of the approximation or, perhaps more accurately said, extend the period over which the approximation is useful. Several ‘ramp’ circuits are reviewed in this note.

Basic RC Ramp

A straightforward approach to generating a ramp voltage is illustrated by the circuit diagram to the right. A square wave applied to the BJT alternately switches the transistor between saturation and cutoff operation. When the transistor is cutoff the capacitor C1 charges exponentially through R2, with a time constant R2 C1. On the other hand if the transistor is turned on the capacitor discharges rapidly and the transistor saturates.

The transient response of this circuit was computed for two conditions. The data plotted immediately below is for a pulse width of 1 millisecond and a period of 30 milliseconds. The period is several time constants in width so as to make the exponential nature of the RC charging clearly evident.

Only the initial part of the exponential rise, a period short compared to one time constant, is ‘linear’ to any extent. In practice the pulse duration would be considerably shorter, just long enough allow for just the initial part of the charging cycle. To illustrate this the circuit response was recomputed, this time for a pulse width of 50 µseconds and a period of just 0.5 millisecond, about one tenth the time constant. The computed data is plotted below. Comparison of the computed data with expected performance is left as an exercise.
Current-Pumped Ramp

RC charging is, as was noted, fundamentally exponential rather than linear. The ramp is approximately linear only for an initial period short compared with a time constant, i.e., the initial part of the exponential rise. The difficulty with RC charging is that as the voltage across the capacitor increases, the voltage difference across the charging resistor decreases, and so also does the charging current. Hence the capacitor charges at a continually decreasing rate.

One way to avoid this difficulty is to charge the capacitor with a constant current source. The circuit (left) replaces the charging resistor of the previous illustration with a (nearly) constant current source formed by the transistors Q2 and Q3. The diode-connected transistor Q3 is used to define the Q3 emitter current, and assuming a good match between Q2 and Q3, cause Q2 to carry the same emitter current. (The Q2 current is not quite constant because of the small dependence of Q2 collector current on collector voltage (Early effect). Even so the linearity over an increased voltage range is apparent in the computed performance plotted to the right.
‘Bootstrap’ Ramp
An intriguing type of ramp generator applies positive feedback to extend the range of linear operation of an RC charging circuit. The circuit diagram on the left side of the figure below suggests a conceivable (but unworkable) approach. RT and CT form a RC charging circuit with time constant $R_T C_T$. A switch periodically closes momentarily to discharge the capacitor and initiate the capacitor charging cycle. The capacitor voltage would rise linearly if the charging current were (somehow) constant. This would be so if, for example, a fixed voltage were applied across RT. But then the voltage at the upper end of RT would have to increase continuously since the voltage across CT increases as the capacitor charges. The circuit illustrated below is an ingenious method for doing just that.

In the circuit on the left (above) a voltage follower is used to copy the voltage across CT without (ideally) loading the capacitor. The voltage across RT is VCC, and because of the voltage follower action remains even as the capacitor charges. Momentarily closing the switch discharges the capacitor and initiates the charging cycle.

A more practical version of this connection is illustrated in the center diagram. Instead of a battery a capacitor CS is used. If the time constant associated with CS is much greater than that associated with CT, i.e. $CS >> CT$, then in a given period voltage changes across CS will be much smaller than those across CT. To the extent that the voltage across CS is essentially constant this capacitor acts as a sort of temporary battery. It is of course necessary to assure that the capacitor is appropriately charged to provide the equivalent of the battery voltage. It is not feasible to connect VCC directly to CS, since the voltage at the RT-CS node is supposed to change. A buffer resistor might be used but there are conflicting requirements for its size. The resistance should be ‘large’ so that it does not significantly affect the timing for the charging, and it should be ‘small’ so that recharging CS occurs quickly. These conflicting requirements are met by use of a diode. CS charges quickly to VCC (less the diode voltage drop) through the diode. Then as the voltage across CT rises so also does the voltage at the base of the diode, and the diode becomes reverse-biased.

To summarize:
A capacitor CS is charged, and used a sort of temporary voltage source. The voltage follower provides a high resistance connection from CT that copies the capacitor voltage to one end of CS. While CT is being discharged (closed switch) CS is charged through the diode by the VCC source. The diode is used to enable charging of CS by the source but prevent a converse current flow. CS charges to somewhat less than VCC because of the diode junction voltage drop. When the switch is opened CT charges through RT, and as CT charges the rising voltage at the non-inverting amplifier input is conveyed to CS. Provided CS $>>$ CT, i.e., is associated with a much larger time constant, it will discharge much more slowly than CT. Hence the voltage at the other end of RT rises, and the diode becomes reverse-biased. Thereafter it is actually CS that supplies the current that charges CT. In effect
CS (and the voltage follower) is being used in a fashion as battery to produce a nearly constant current through RT.

Note that the feedback is positive, i.e. as the voltage across CT rises feedback provided through the voltage follower applies a voltage to further increase the voltage. However the process necessarily terminates itself since the opamp will saturate eventually. A connection of this sort is commonly called a 'bootstrap' connection after the tongue-in-cheek suggestion that people can lift themselves off the ground by pulling up on their own bootstraps.

When the switch is closed CS charges very quickly through the diode. The equivalent (LaPlace) circuit (idealized opamp) for the charging cycle is drawn on the right of the previous figure. It can be shown that

\[ v(t) = \frac{V_{CC} C_S}{C_T} \left[ 1 - e^{-t/(RTCS)} \right] \]

Note that the charging remains exponential, characteristic for a RC charging. The bootstrap effect appears in the time constant, which involves not CT but the (larger) capacitance CS. For \( t << RTCS \) the exponential can be approximated as \( 1 - \frac{t}{RTCS} + \ldots \), and

\[ v(t) \approx V_{CC}\left(\frac{t}{RTCT}\right) \]

Note again the underlying assumption of \( C_S >> CT \).

A bootstrap circuit design is illustrated to the right. The switch is provided by a transistor driven between saturation (low collector-emitter voltage approximating zero volts) and cutoff (approximating an open-circuit) by a pulse voltage input. The base resistor is used to limit the base current to safe values. Switching is done by a 0.3 milisecond pulse with a 1.5 milisecond period.

PSpice performance computations for the circuit are drawn below. Comparison of the computations against expectations is left as exercise.