

RESISTOR

Despite the simplicity of resistors, the actual current carrier in a carbon resistor, is unclear, at least to me. No one cares very much I suspect, because the device works nearly perfectly. The carrier of charge does not matter very much. What matters is the constitutive law that describes the relation of current, voltage and time. The constitutive law should satisfy conservation of mass, charge and current.

It is instructive to write the constitutive law for a resistor Ohm's law for only particle current, using a conservation of particle (mass) formulation, and then write it again for particle plus displacement current (from one terminal to another). If you apply a step function of current (or potential for that matter), to the purely particle formulation, a paradox arises. The potential changes but the particle current flowing into the resistor from the left is exactly equal to the particle current flowing out on the right **at all times**. Why does the potential change if there is no accumulation of charge?

The paradox can be resolved in two (nearly) equivalent ways. (1) The constitutive equation Ohm's law can be used with the extended definition of current that includes the displacement current. In that case there is continuity of generalized current, but there is NOT continuity of particle current at all times. The transient accumulation of particle current provides the charge that changes the potential. Paradox resolved. (2) Alternatively, the circuit model of the resistor in Fig. 2 can be changed to have an explicit capacitor in parallel with it. In that case, the charge accumulates on the capacitor, and the resistor itself can have continuity of flux of particles at all times and follow Ohm's law using the current/flux of particles (and not the displacement current). The charge on the capacitor creates and changes the electric field. Paradox resolved.

Maxwell himself repeatedly used capacitors in this spirit (Sections 102, 125, 199, and Chapters 8, are some examples, in [116]) to understand the role and significance of displacement current. We (following the insight and advice of Wolfgang Nonner) have used capacitors as a crude way to connect permanent charges (specifically, acid side chains in a channel protein away from the pore) and electrical potential in the pore of a channel protein, e.g., the potassium channel.[45]