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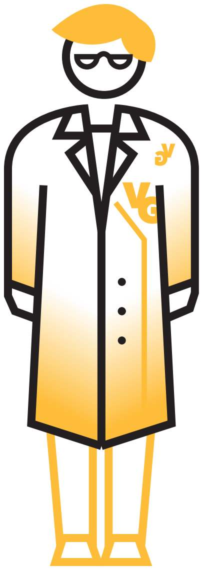

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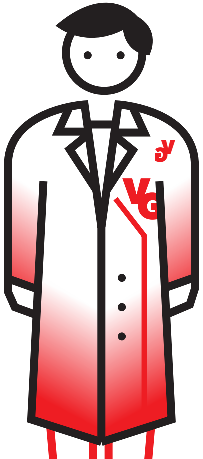

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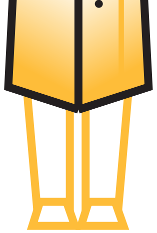

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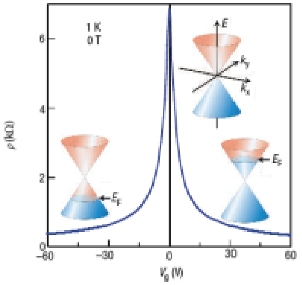

Figure 3 Ambipolar electric field effect in single-layer graphene. The insets show its conical low-energy spectrum $E(k)$, indicating changes in the position of the Fermi energy E_F with changing gate voltage V_g. Positive (negative) V_g induce electrons (holes) in concentrations $n = \alpha V_g$ where the coefficient $\alpha \approx 7.2\times10^{10}$ cm^{-2} V^{-1} for field-effect devices with a 300 nm SiO$_2$ layer used as a dielectric[7–9]. The rapid decrease in resistivity ρ on adding charge carriers indicates their high mobility (in this case, $\mu \approx 5{,}000$ cm^2 V^{-1} s^{-1} and does not noticeably change with increasing temperature to 300 K).

Although there is nothing particularly relativistic about electrons moving around carbon atoms, their interaction with the periodic potential of graphene's honeycomb lattice gives rise to new quasiparticles that at low energies E are accurately described by the (2+1)-dimensional Dirac equation with an effective speed of light $v_F \approx 10^6$ m^{-1}s^{-1}. These quasiparticles, called massless Dirac fermions, can be seen as electrons that have lost their rest mass m_0 or as neutrinos that acquired the electron charge e. The relativistic-like description of electron waves on honeycomb lattices has been known theoretically for many years, never failing to attract attention, and the experimental discovery of graphene now provides a way to probe quantum electrodynamics (QED) phenomena by measuring graphene's electronic properties.

QED IN A PENCIL TRACE

From the point of view of its electronic properties, graphene is a zero-gap semiconductor, in which low-E quasiparticles within each valley can formally be described by the Dirac-like hamiltonian

$$\hat{H} = \hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = \hbar v_F \,\sigma\cdot\mathbf{k}\,, \tag{1}$$

where $\mathbf{k}$ is the quasiparticle momentum, σ the 2D Pauli matrix and the k-independent Fermi velocity v_F plays the role of the speed of light. The Dirac equation is a direct consequence of graphene's crystal symmetry. Its honeycomb lattice is made up of two equivalent carbon sublattices A and B, and cosine-like energy bands associated with the sublattices intersect at zero E near the edges of the Brillouin zone, giving rise to conical sections of the energy spectrum for $|E| < 1$ eV (Fig. 3).

We emphasize that the linear spectrum $E = \hbar v_F k$ is not the only essential feature of the band structure. Indeed, electronic states near zero E (where the bands intersect) are composed of states belonging to the different sublattices, and their relative contributions in the make-up of quasiparticles have to be taken into account by, for example, using two-component wavefunctions (spinors). This requires an index to indicate sublattices A and B, which is similar to the spin index (up and down) in QED and, therefore, is referred to as pseudospin. Accordingly, in the formal description of graphene's quasiparticles by the Dirac-like hamiltonian above, σ refers to pseudospin rather than the real spin of electrons (the latter must be described by additional terms in the hamiltonian). Importantly, QED-specific phenomena are often inversely proportional to the speed of light c, and therefore enhanced in graphene by a factor $c/v_F \approx 300$. In particular, this means that pseudospin-related effects should generally dominate those due to the real spin.

By analogy with QED, one can also introduce a quantity called chirality[6] that is formally a projection of σ on the direction of motion $\mathbf{k}$ and is positive (negative) for electrons (holes). In essence, chirality in graphene signifies the fact that k electron and $-k$ hole states are intricately connected because they originate from the same carbon sublattices. The concepts of chirality and pseudospin are important because many electronic processes in graphene can be understood as due to conservation of these quantities[6,43–48].

It is interesting to note that in some narrow-gap 3D semiconductors, the gap can be closed by compositional changes or by applying high pressure. Generally, zero gap does not necessitate Dirac fermions (that imply conjugated electron and hole states), but in some cases they might appear[5]. The difficulties of tuning the gap to zero, while keeping carrier mobilities high, the lack of possibility to control electronic properties of 3D materials by the electric field effect and, generally, less pronounced quantum effects in 3D limited studies of such semiconductors mostly to measuring the concentration dependence of their effective masses m (for a review, see ref. 49). It is tempting to have a fresh look at zero-gap bulk semiconductors, especially because Dirac fermions have recently been reported even in such a well-studied (small-overlap) 3D material as graphite[50,51].

CHIRAL QUANTUM HALL EFFECTS

At this early stage, the main experimental efforts have been focused on the electronic properties of graphene, trying to understand the consequences of its QED-like spectrum. Among the most spectacular phenomena reported so far, there are two new ('chiral') quantum Hall effects (QHEs), minimum quantum conductivity in the limit of vanishing concentrations of charge carriers and strong suppression of quantum interference effects.

Figure 4 shows three types of QHE behaviour observed in graphene. The first one is a relativistic analogue of the integer QHE and characteristic of single-layer graphene[9,10]. It shows up as an uninterrupted ladder of equidistant steps in the Hall conductivity σ_{xy} which persists through the neutrality (Dirac) point, where charge carriers change from electrons to holes (Fig. 4a). The sequence is shifted with respect to the standard QHE sequence by ½, so that $\sigma_{xy} = \pm 4e^2/h\ (N + ½)$ where N is the Landau level (LL) index and factor 4 appears due to double valley and double spin degeneracy. This QHE has been dubbed 'half-integer' to reflect both the shift and the fact that, although it is not a new fractional QHE, it is not the standard integer QHE either. The unusual sequence is now well understood as arising from the QED-like quantization of graphene's electronic spectrum in magnetic field B, which is described[45,52–54] by $E_N = \pm v_F\sqrt{2e\hbar BN}$ where ± refers to electrons and holes. The existence of a quantized level at zero E, which is shared by electrons and holes (Fig. 4c), is essentially everything one needs to know to explain the anomalous QHE sequence[52–56]. An alternative explanation for the half-integer QHE is to invoke the coupling between pseudospin and orbital motion, which gives rise to a geometrical phase of π accumulated along cyclotron trajectories, which is often referred to as Berry's

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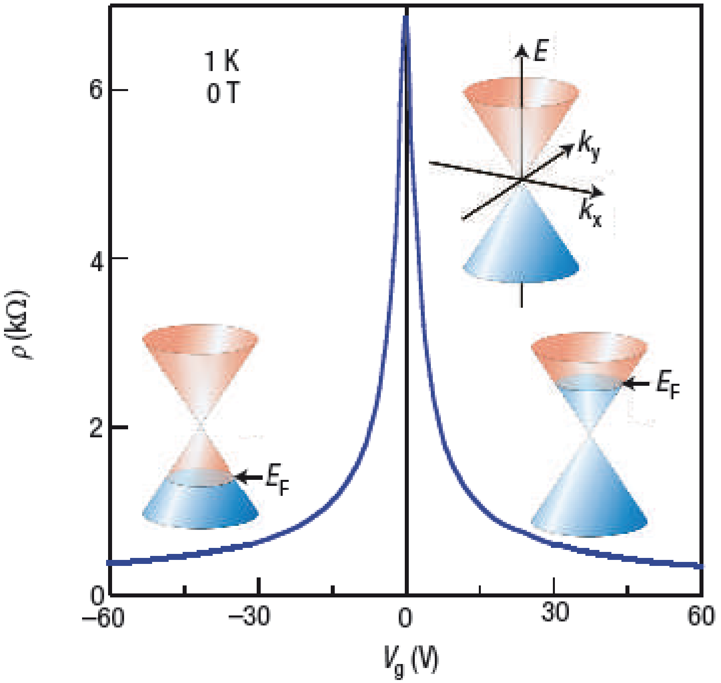

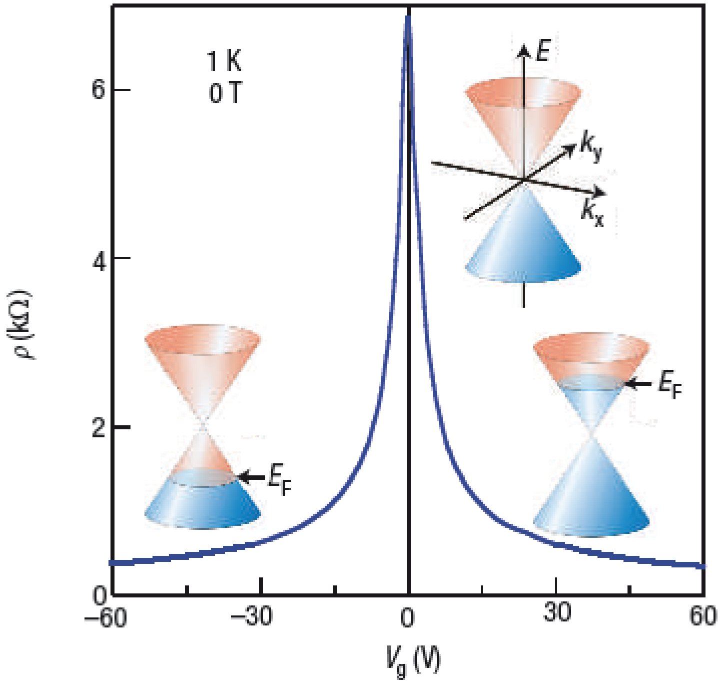
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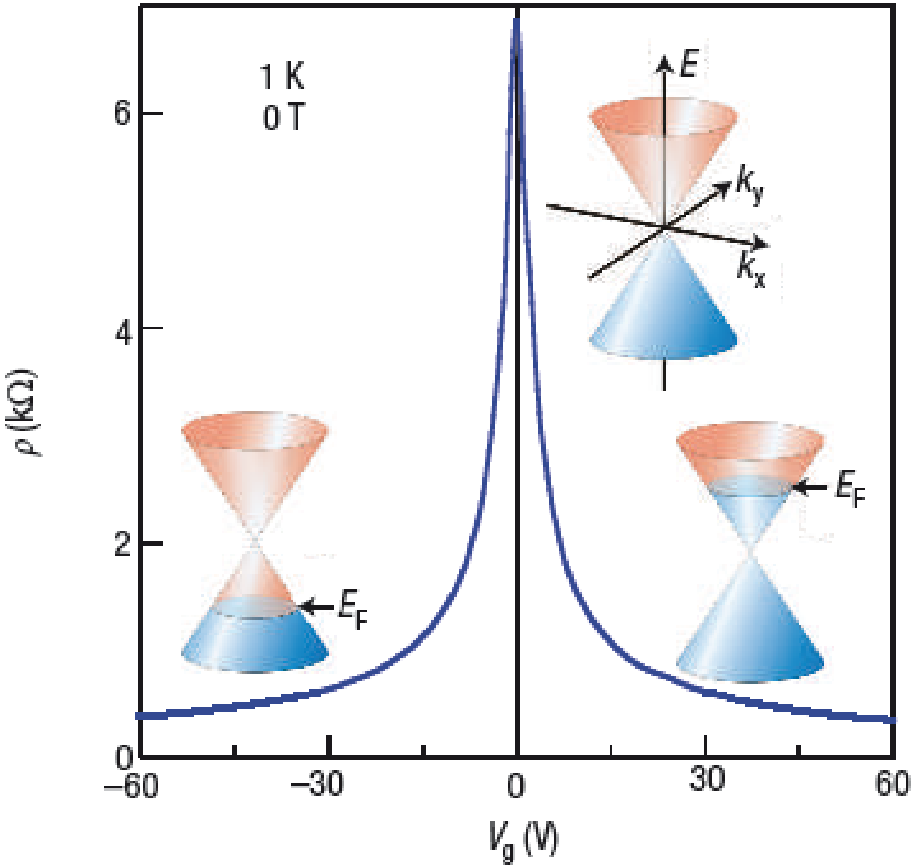
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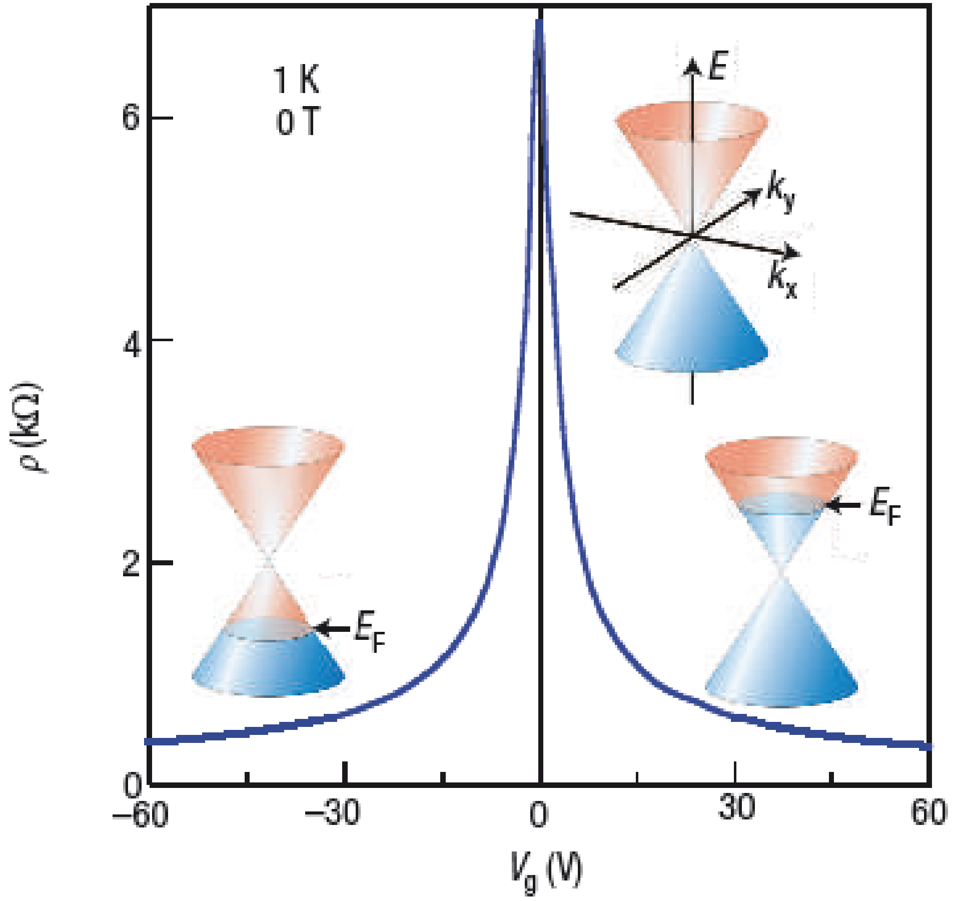
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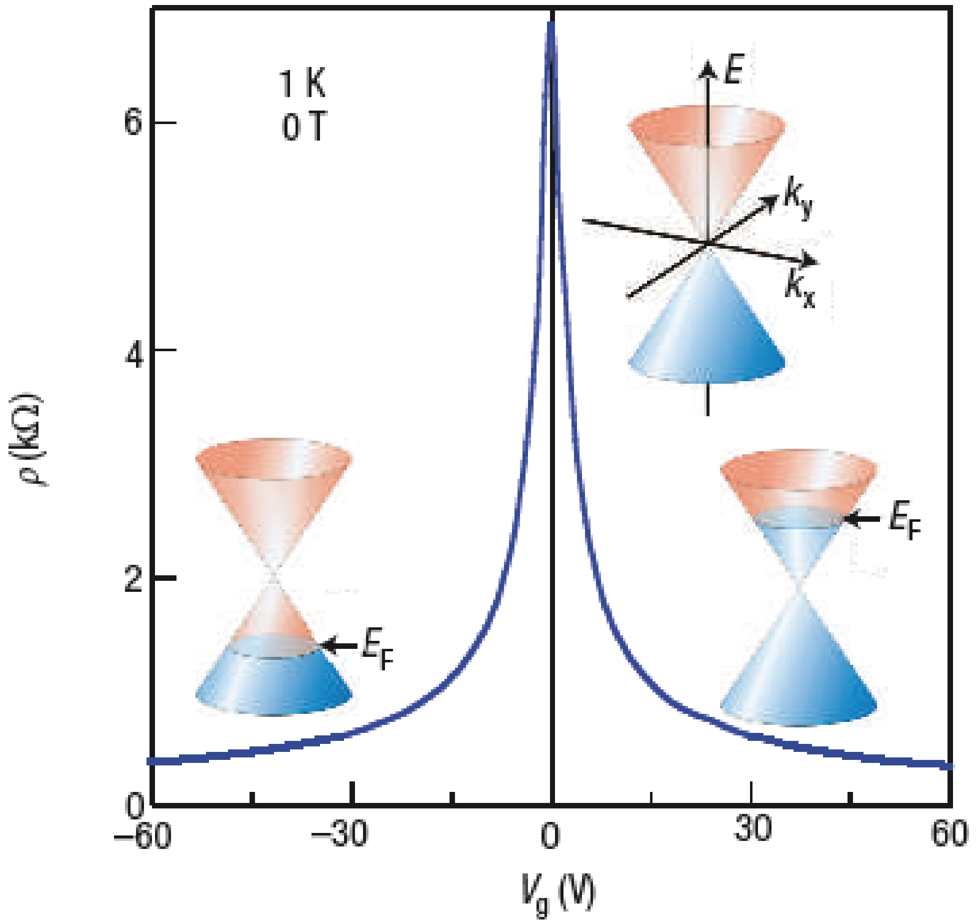
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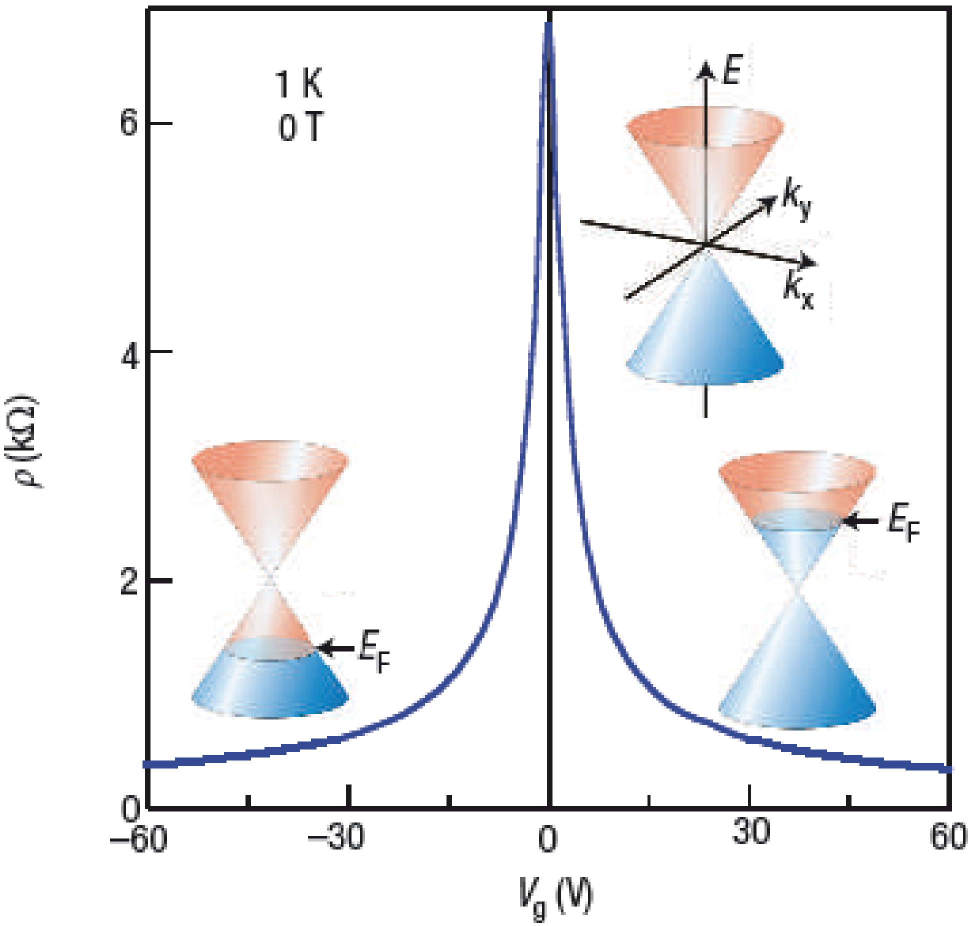
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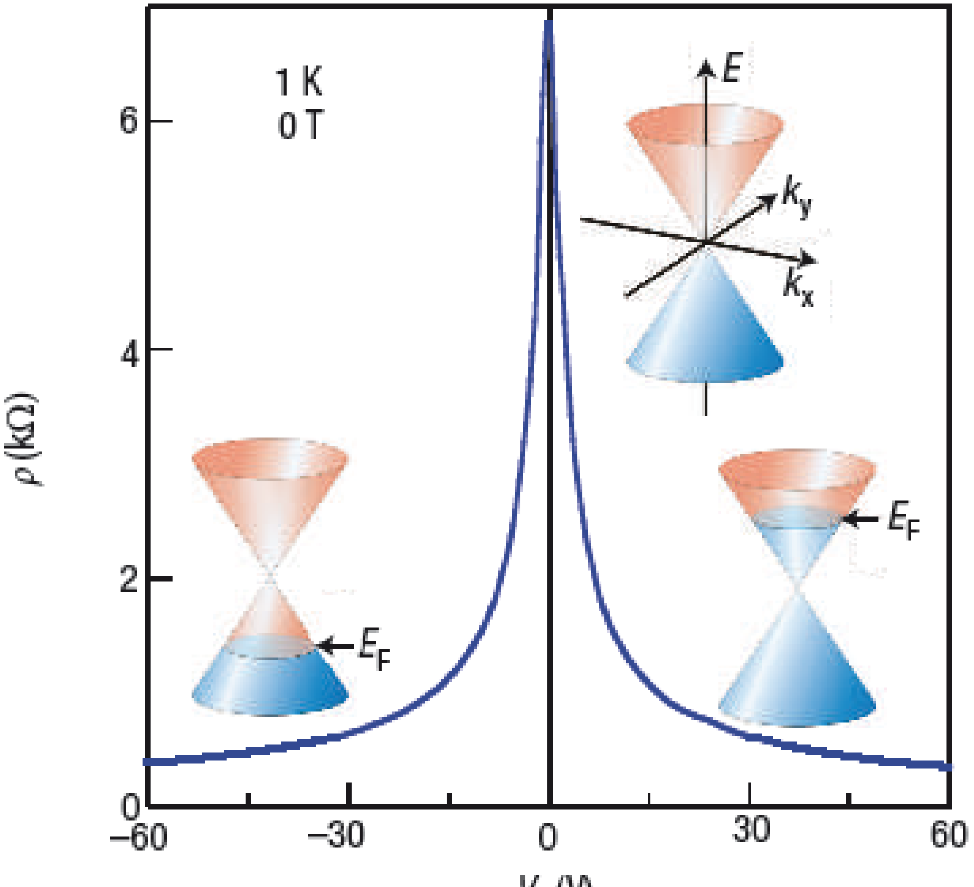

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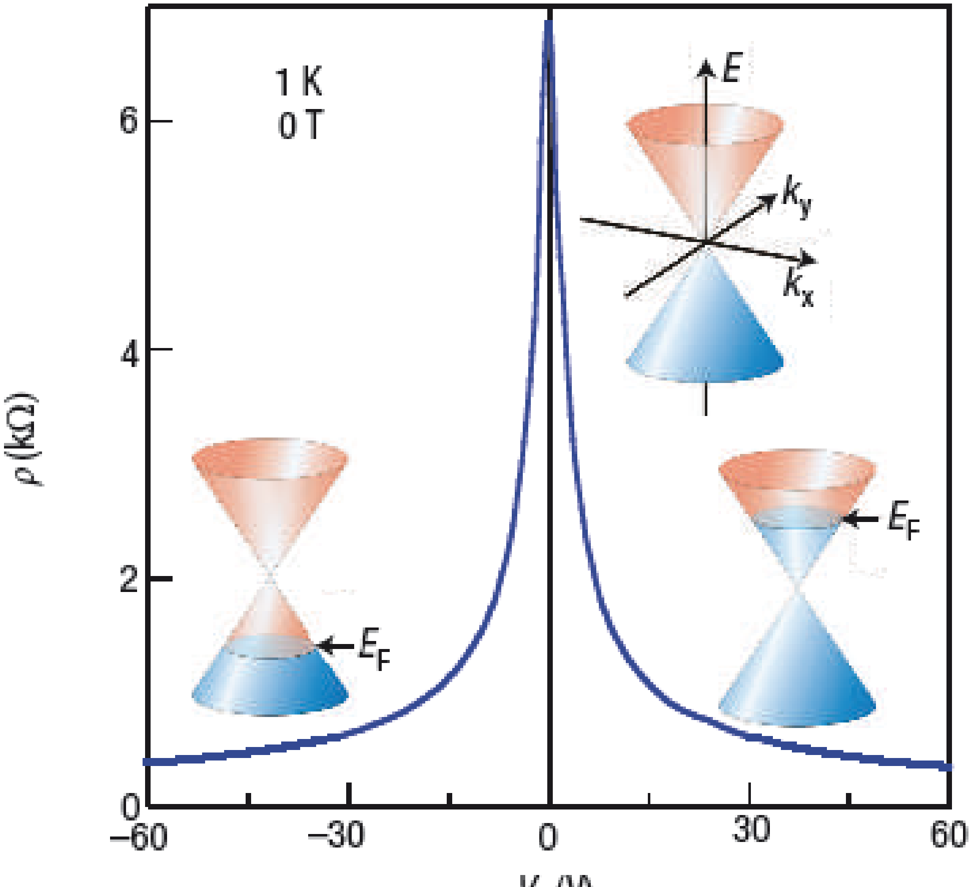
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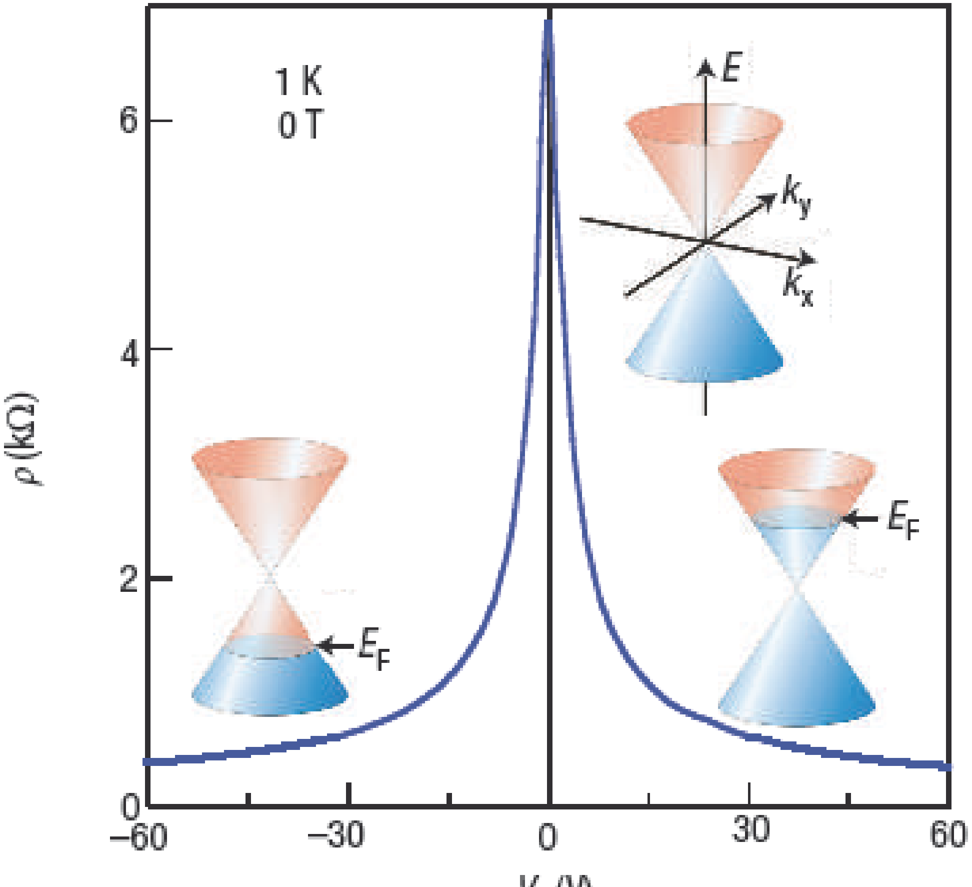
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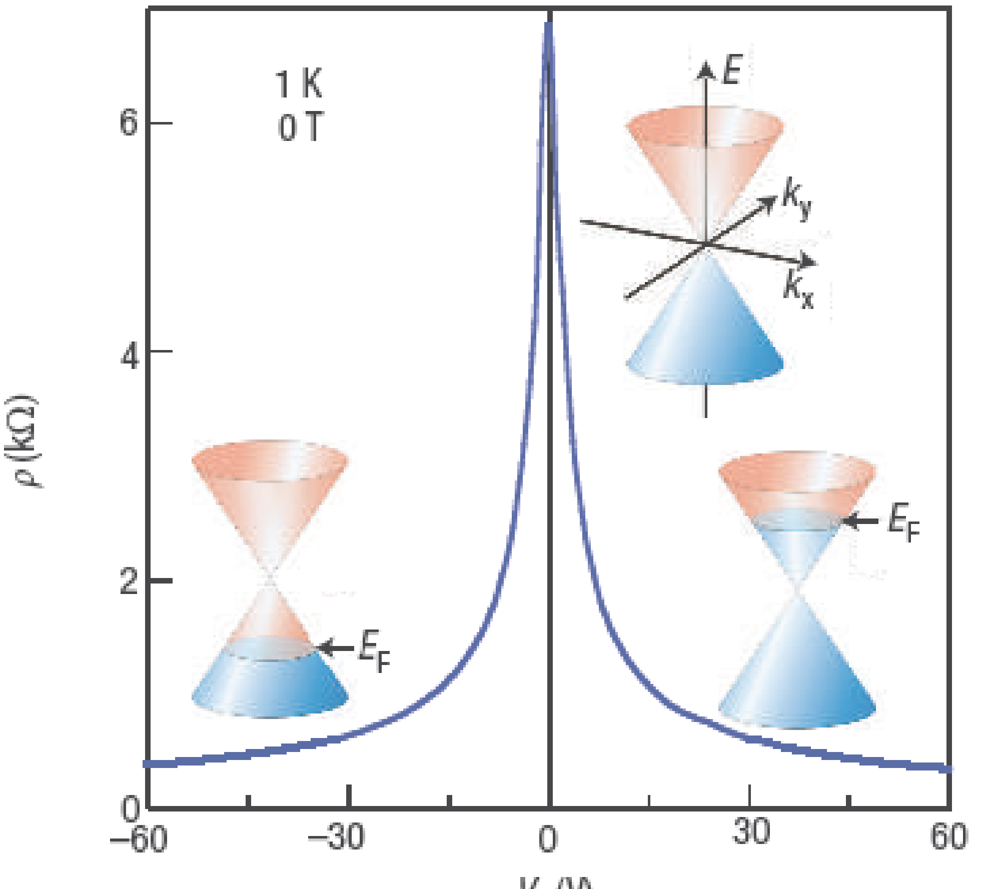
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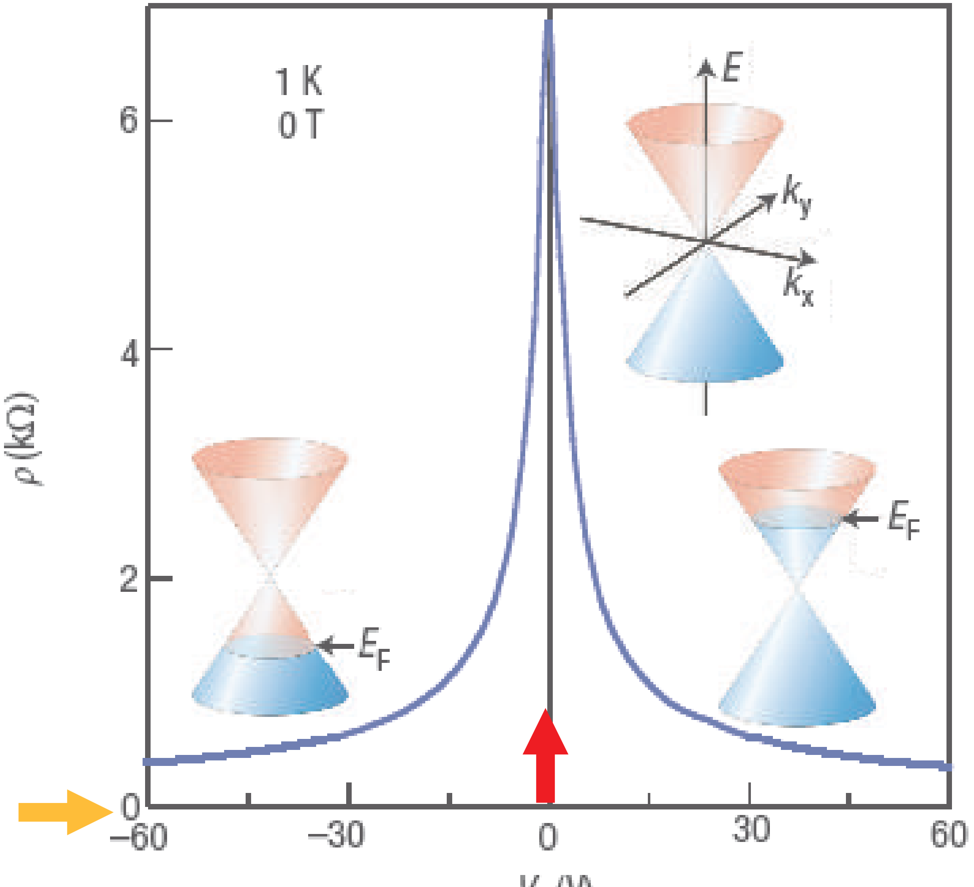

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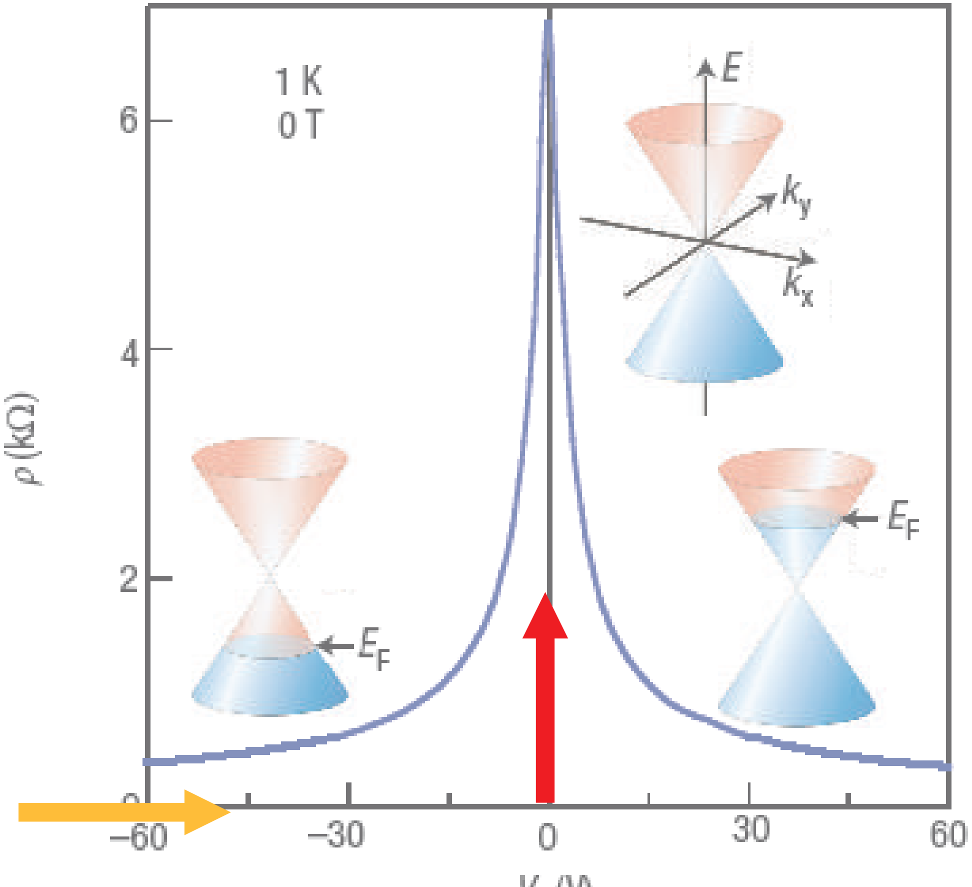

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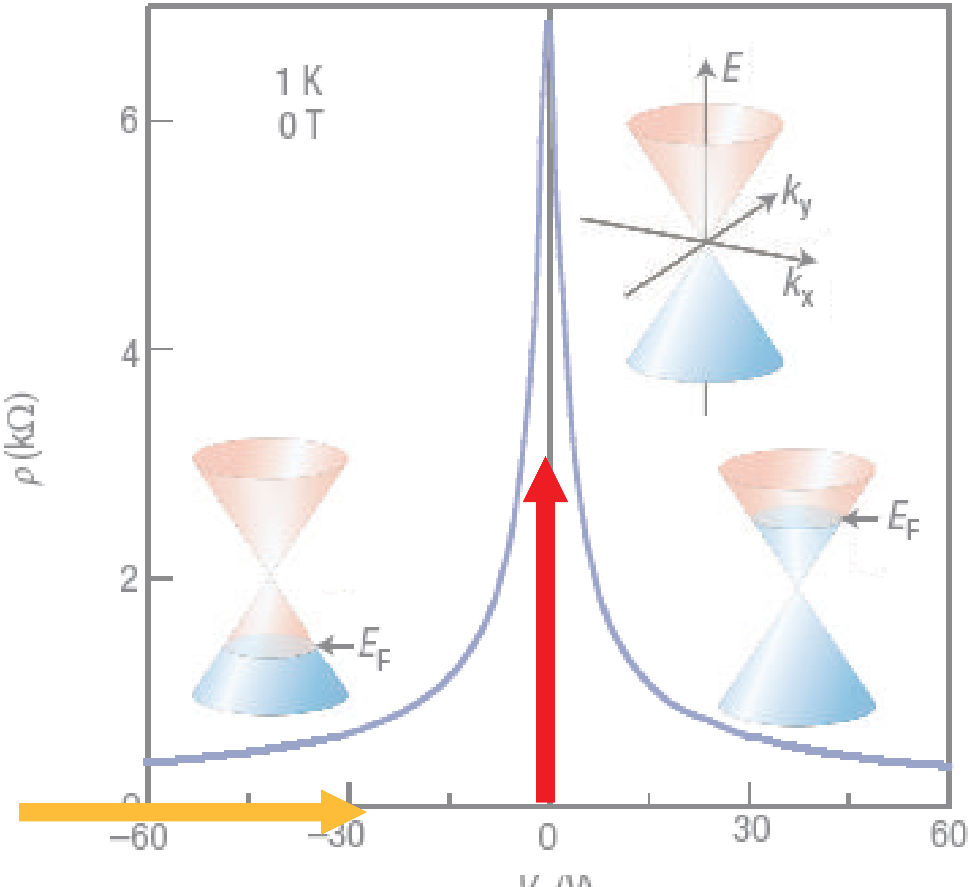

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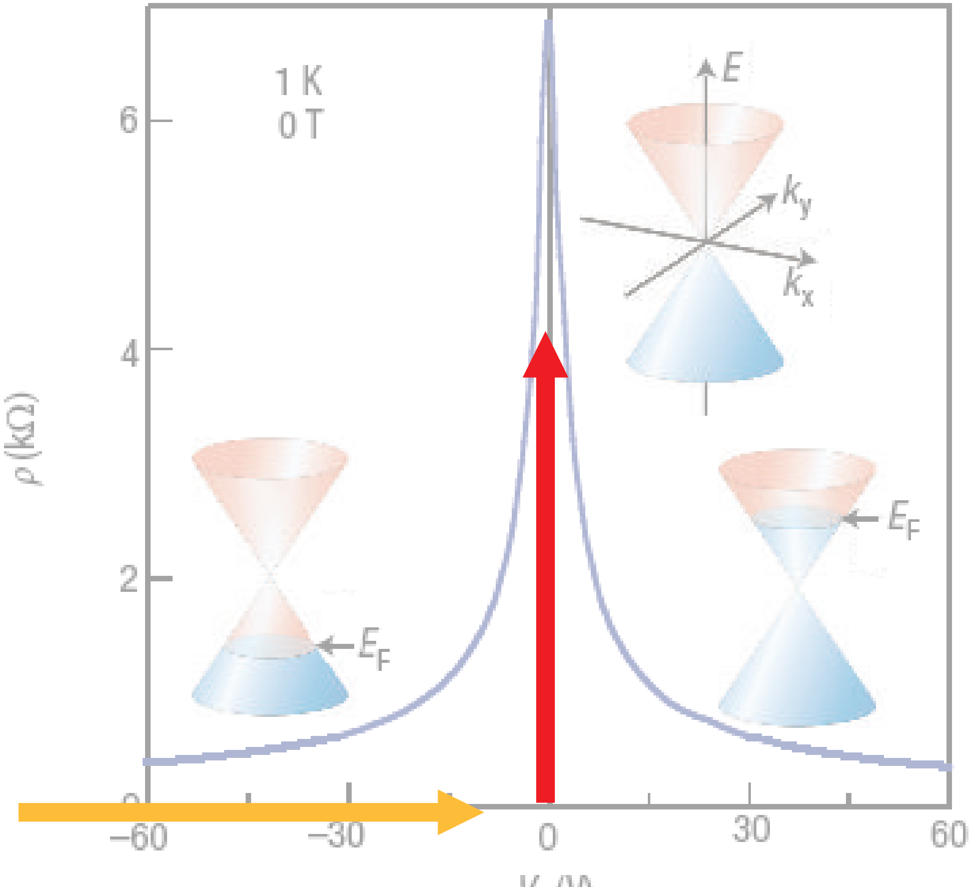

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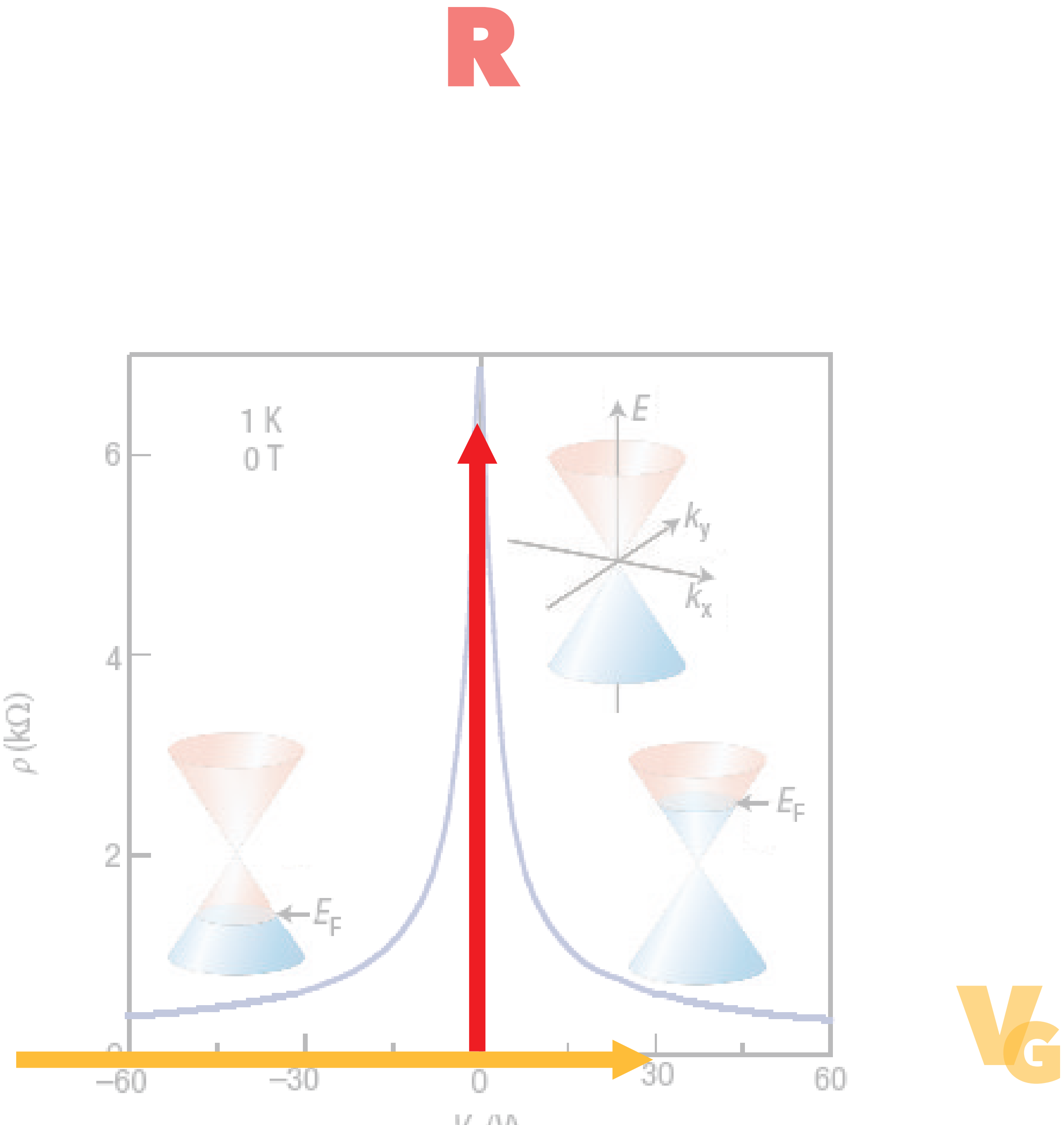
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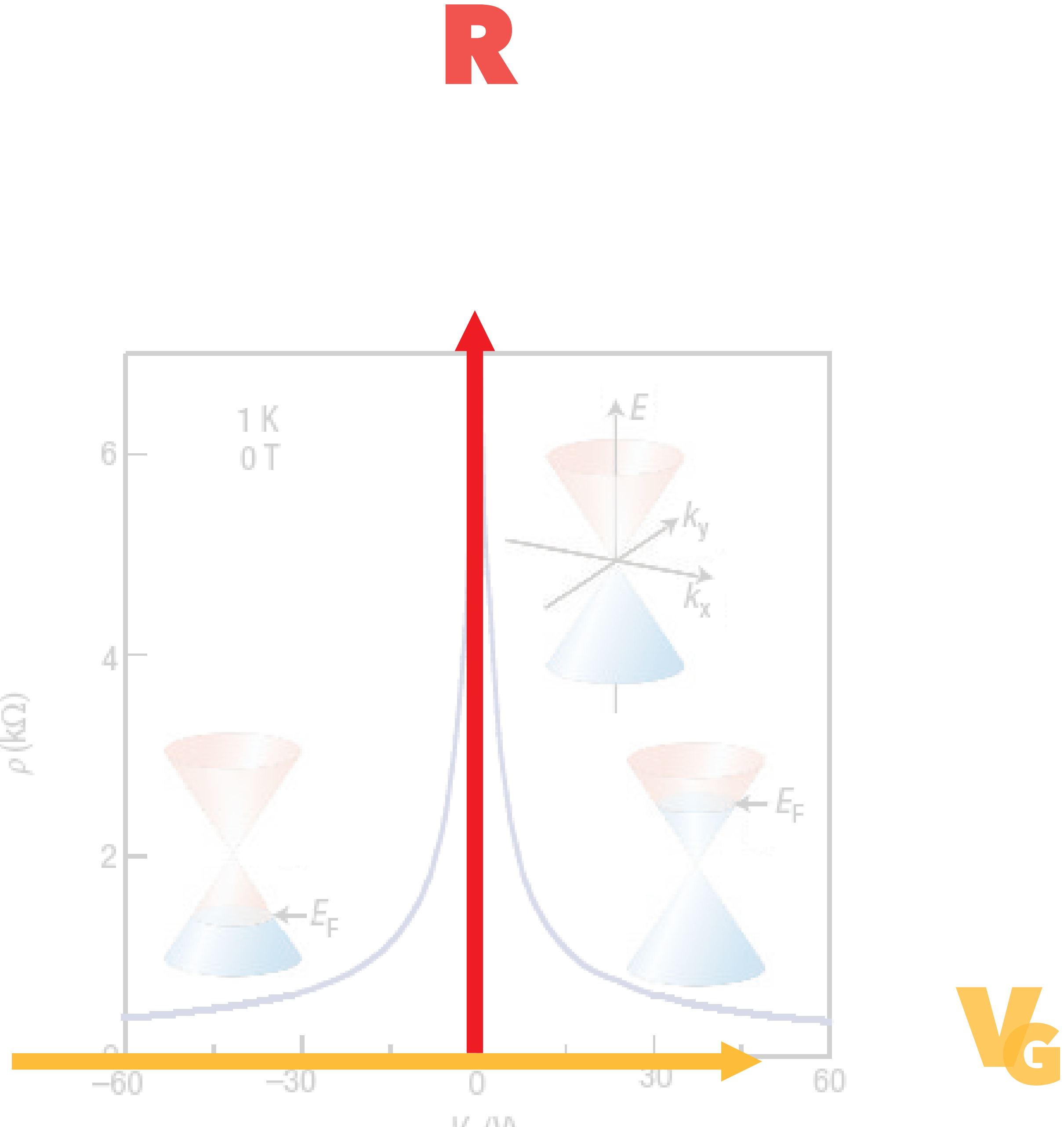
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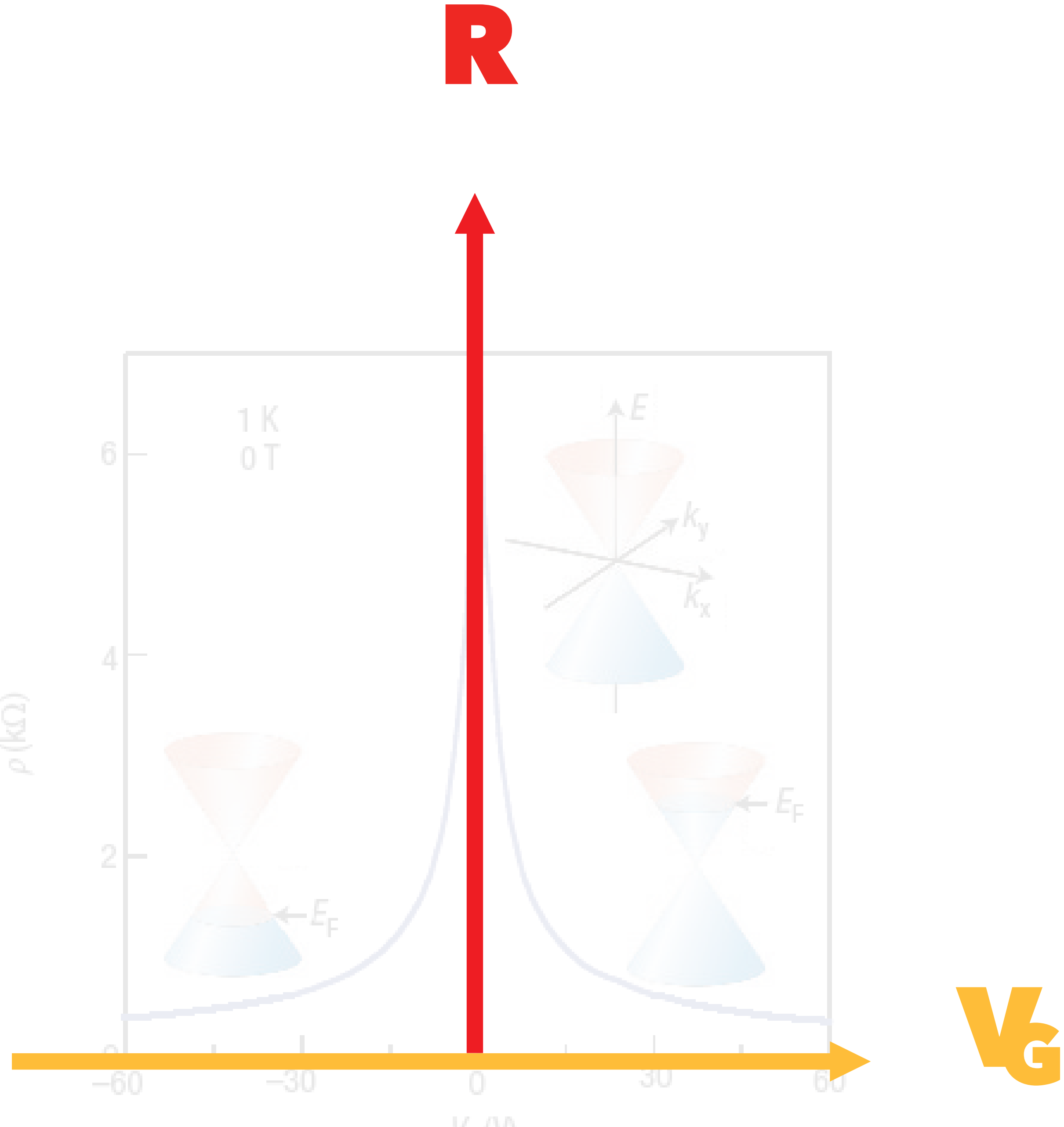
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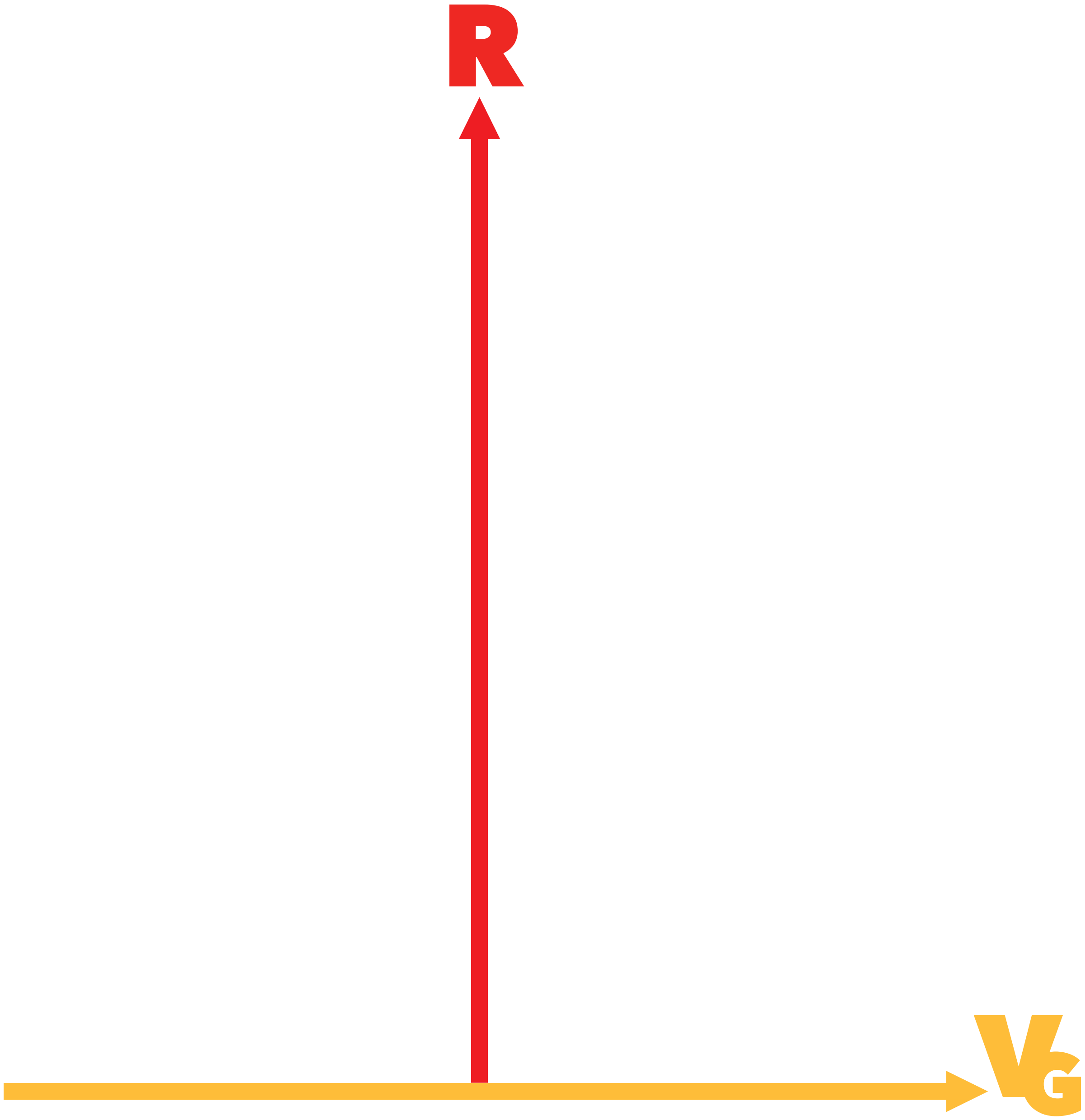
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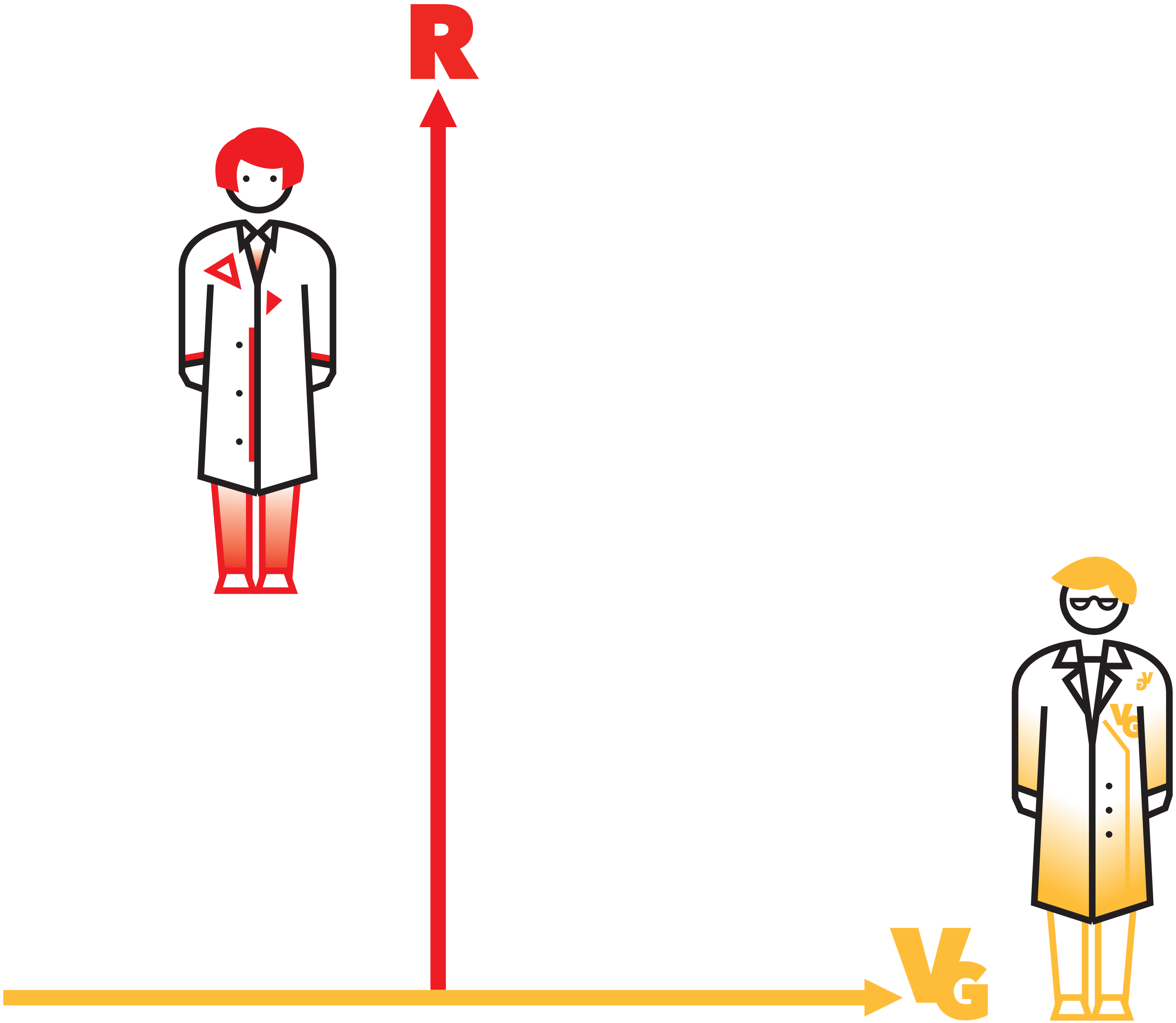
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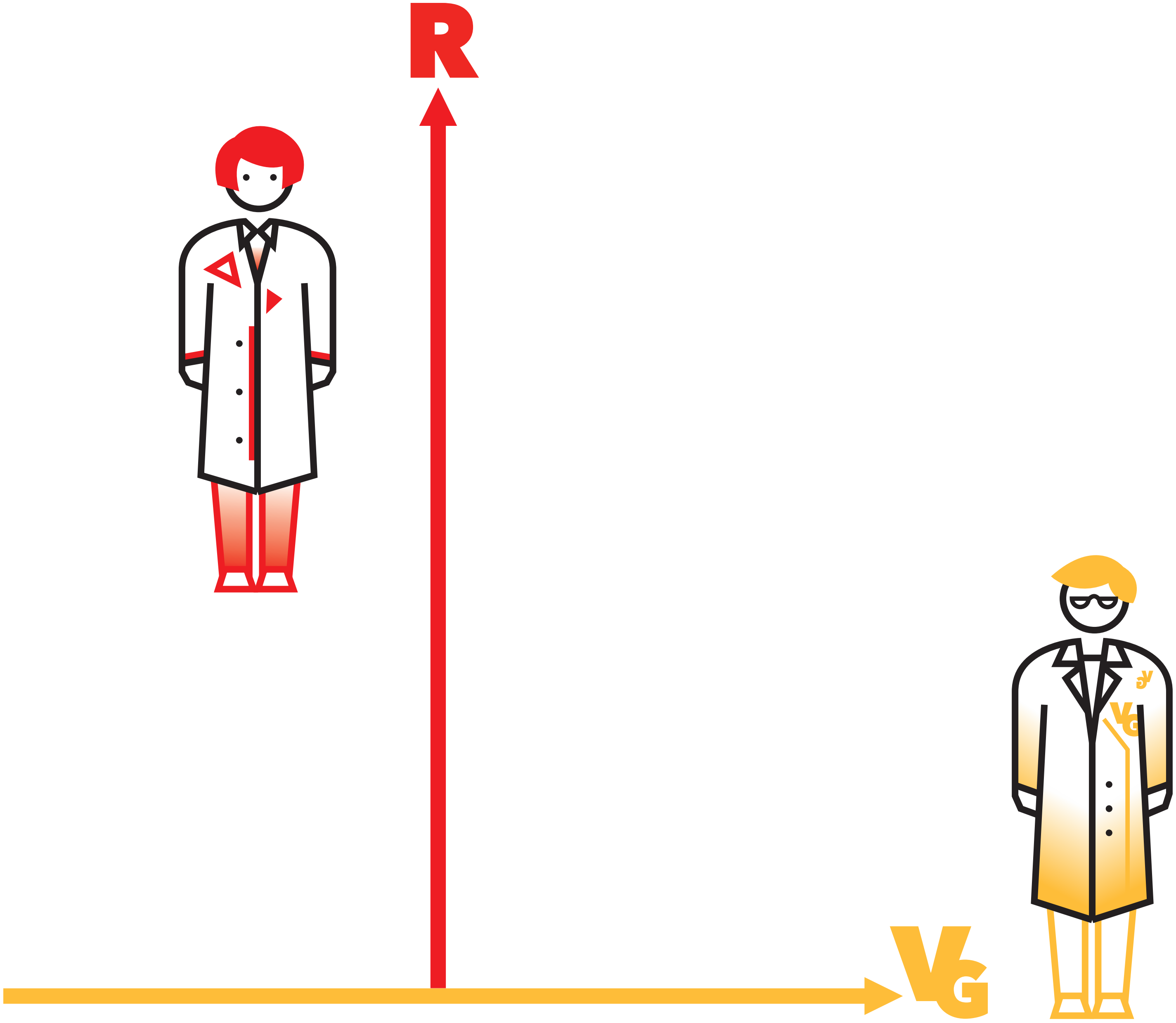
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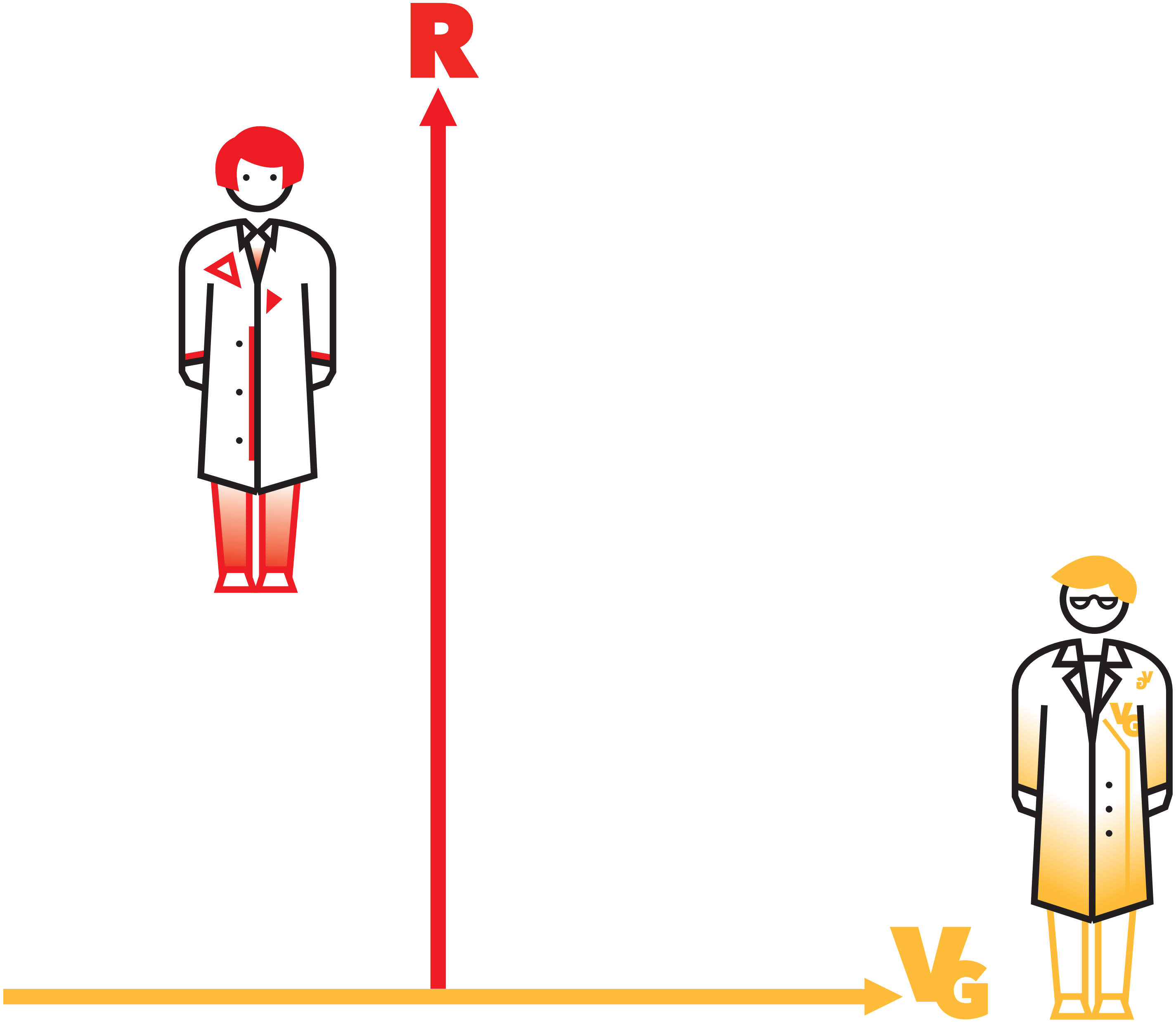
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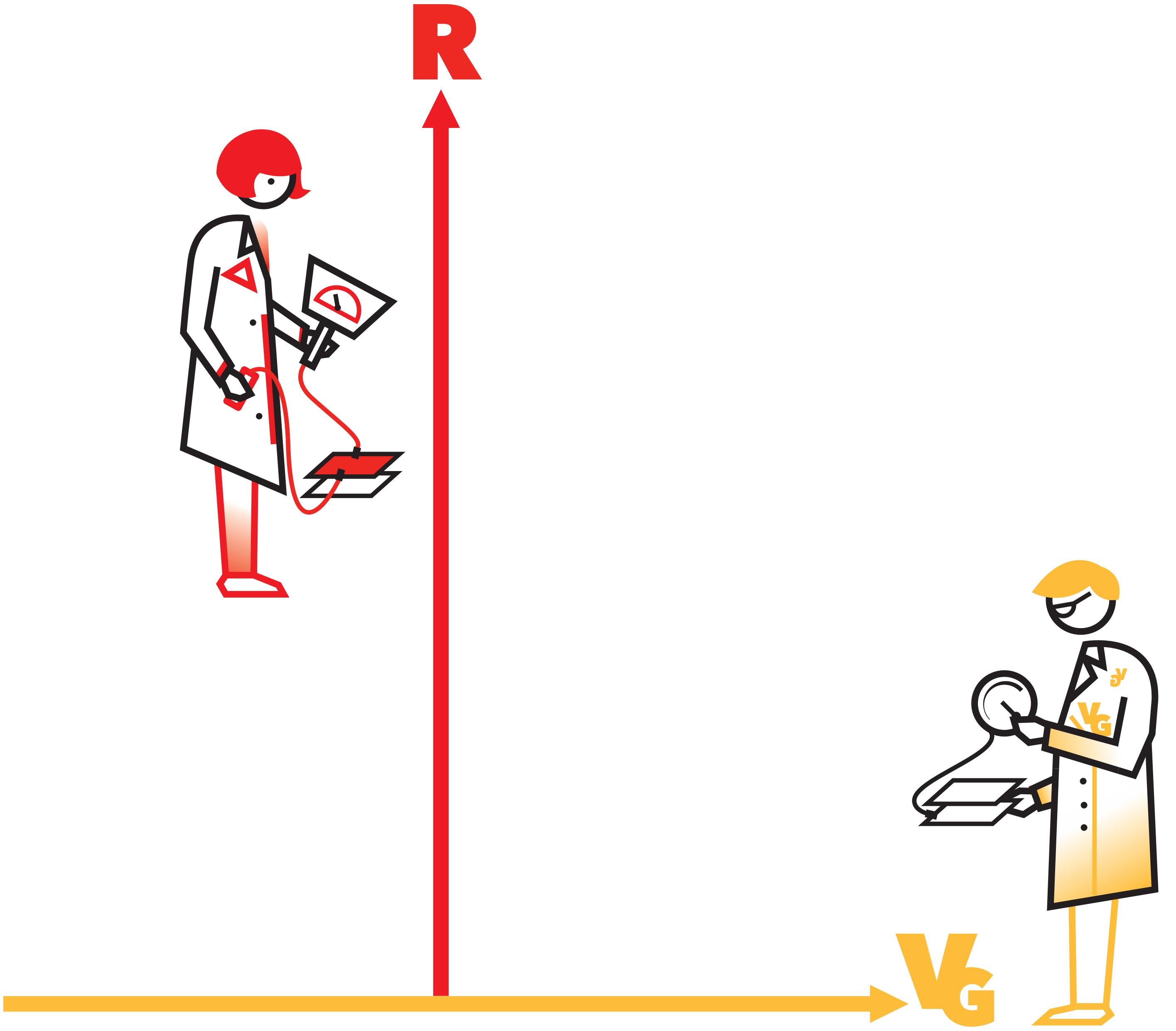
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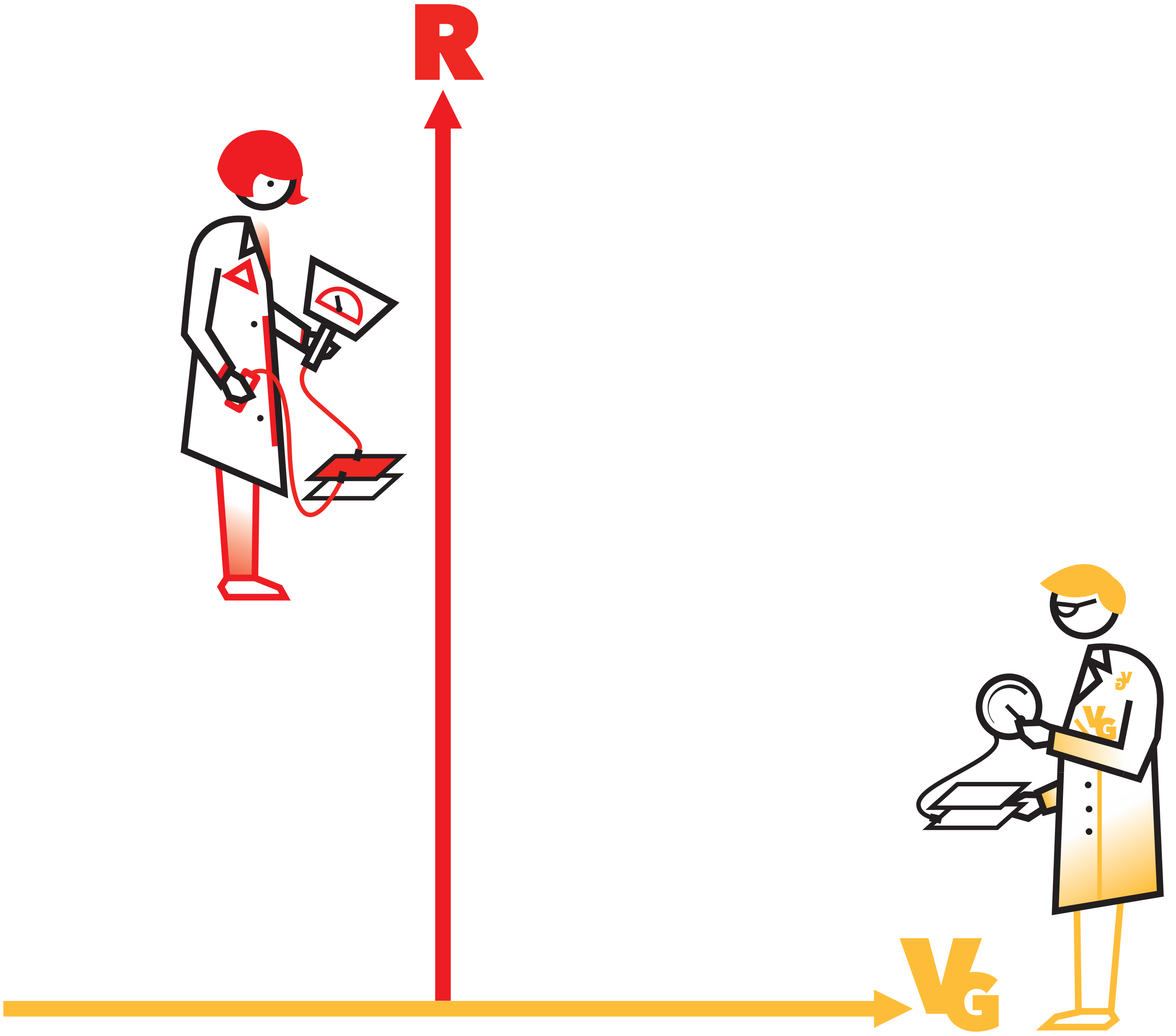
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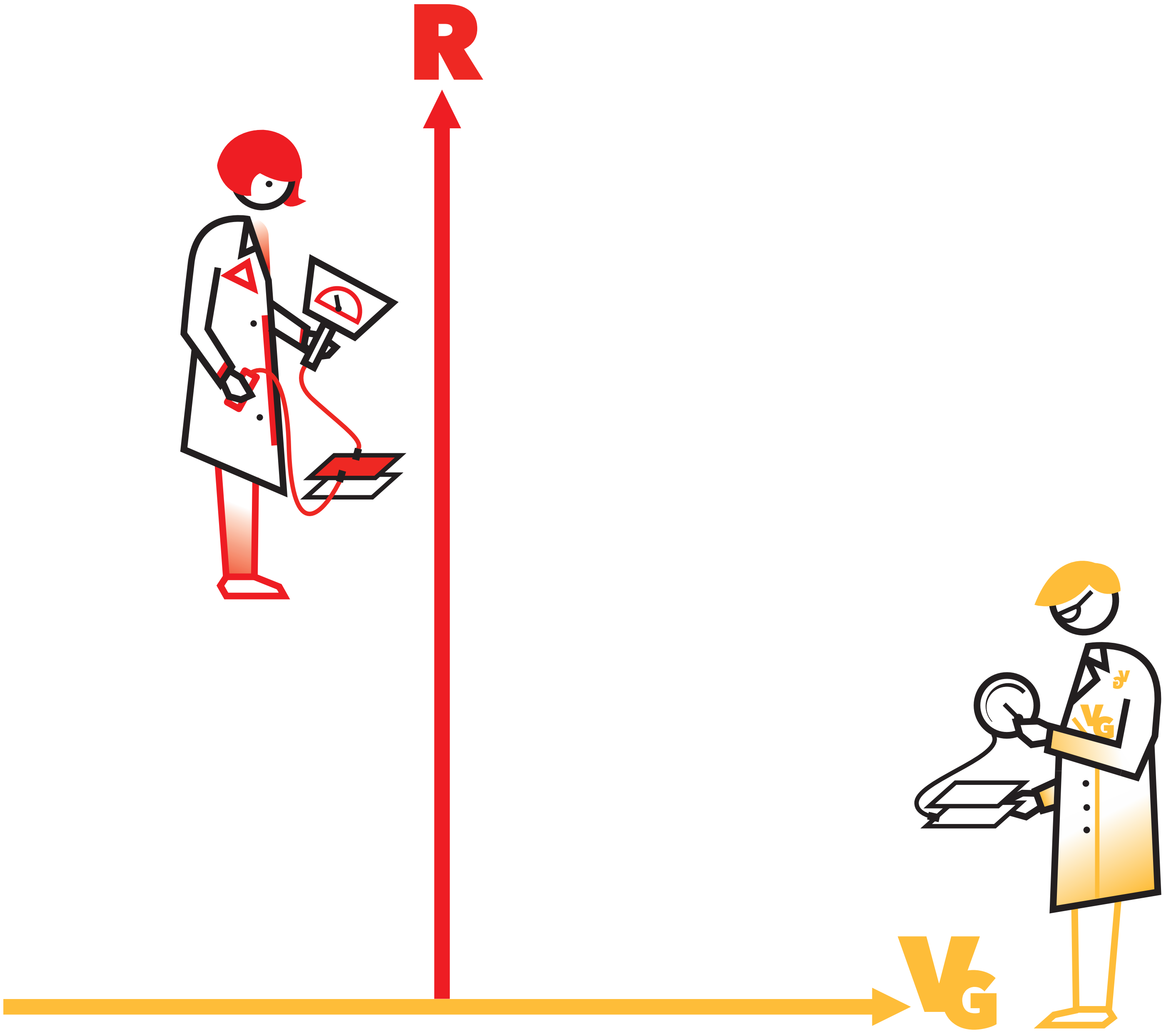
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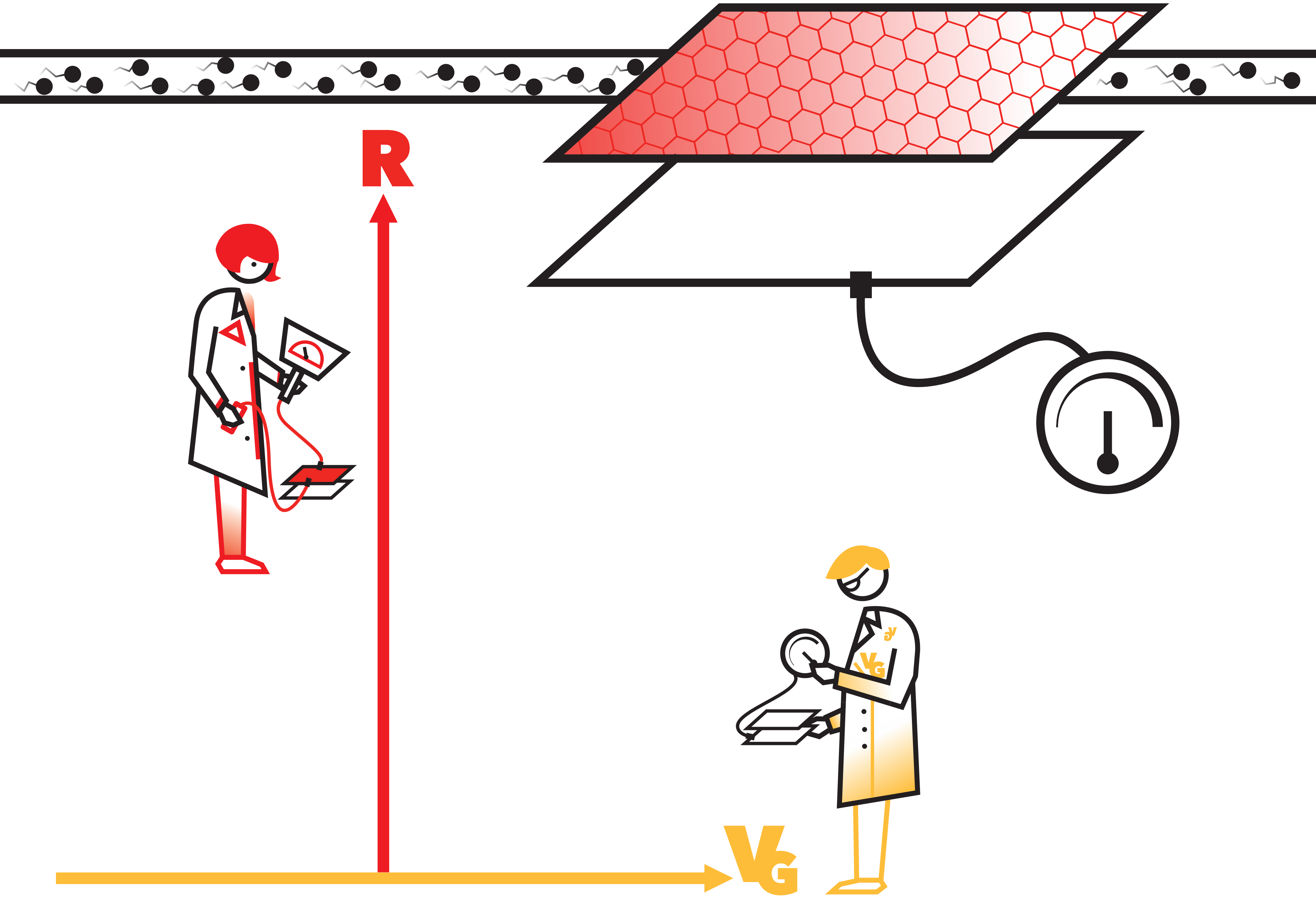
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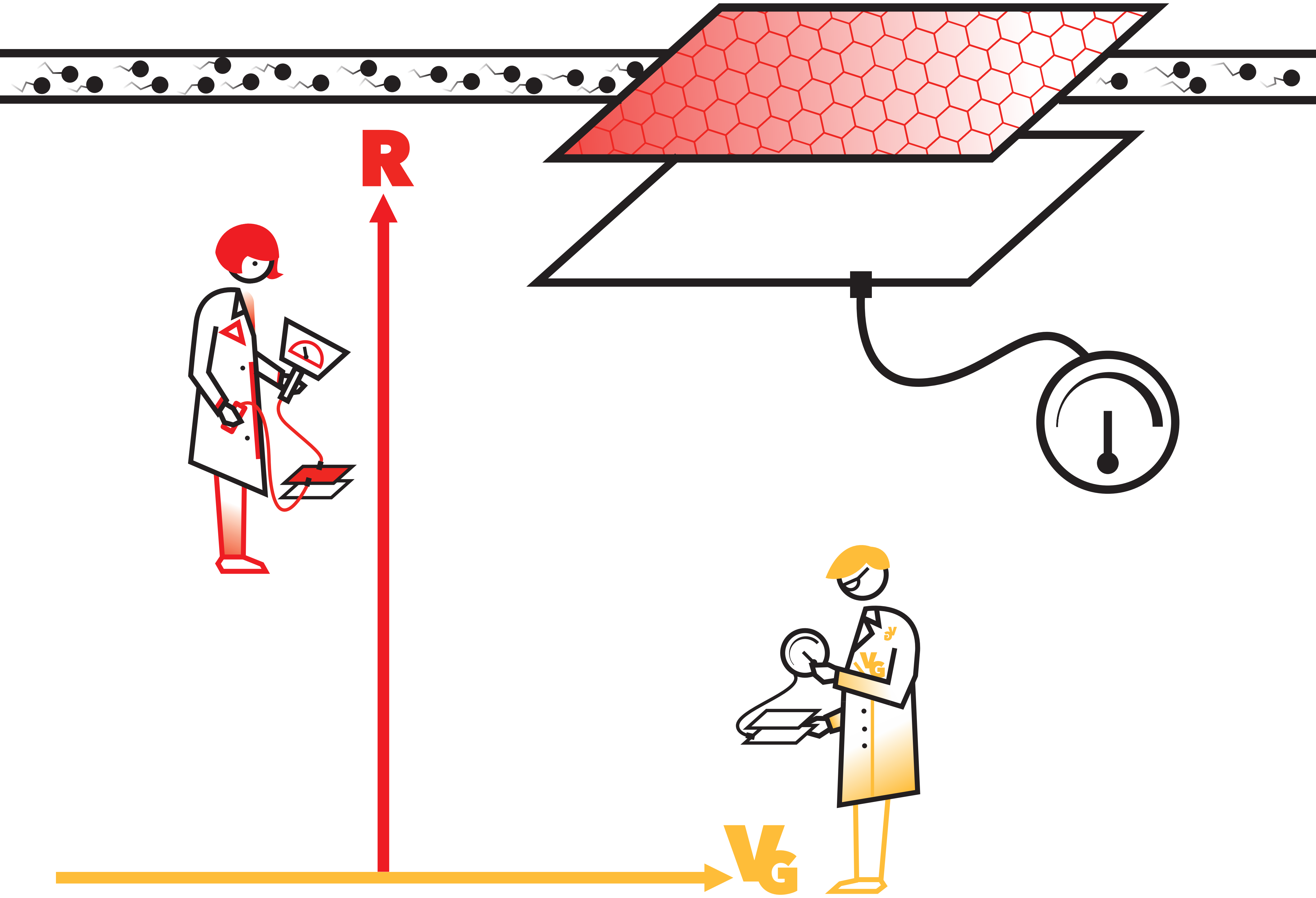
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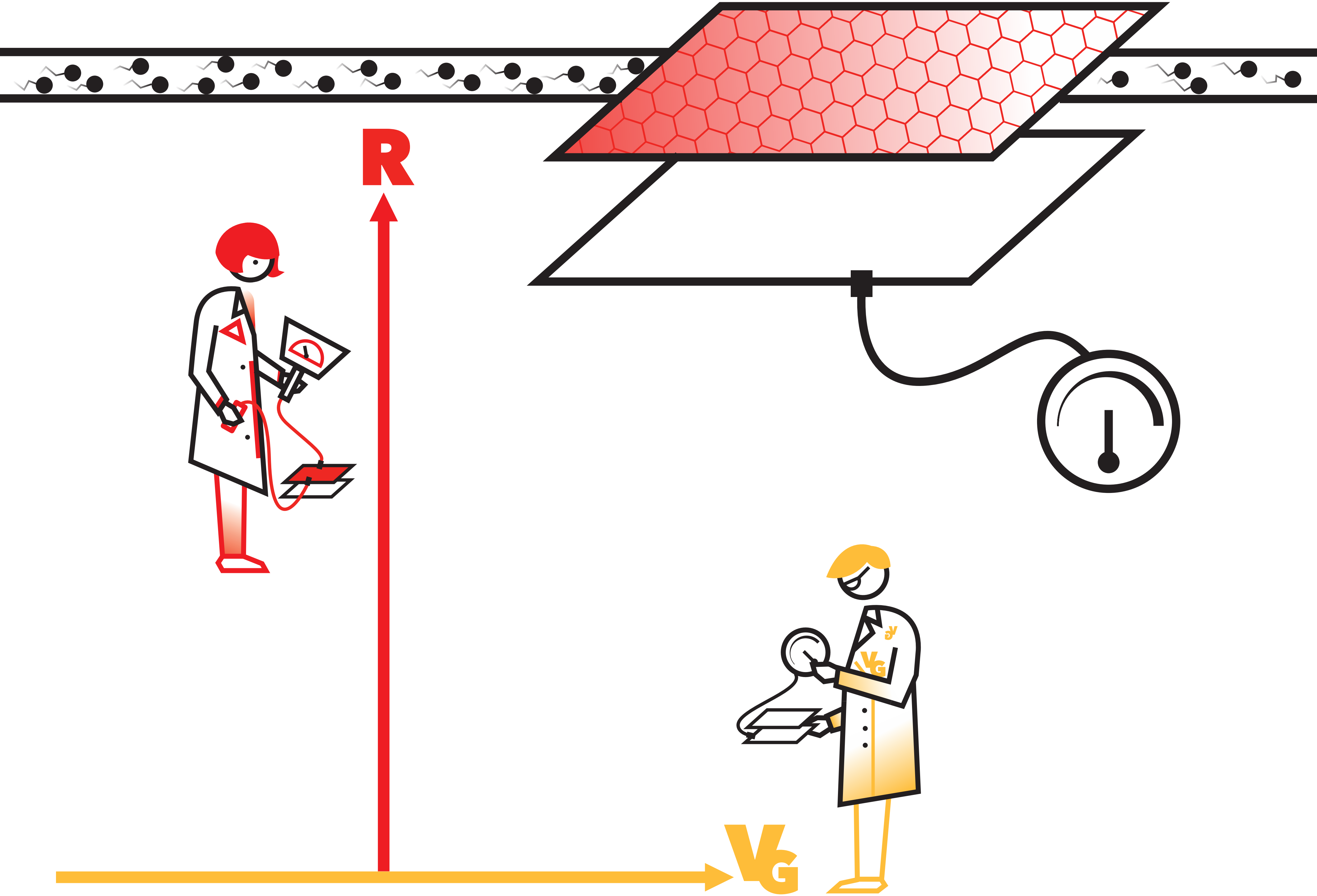
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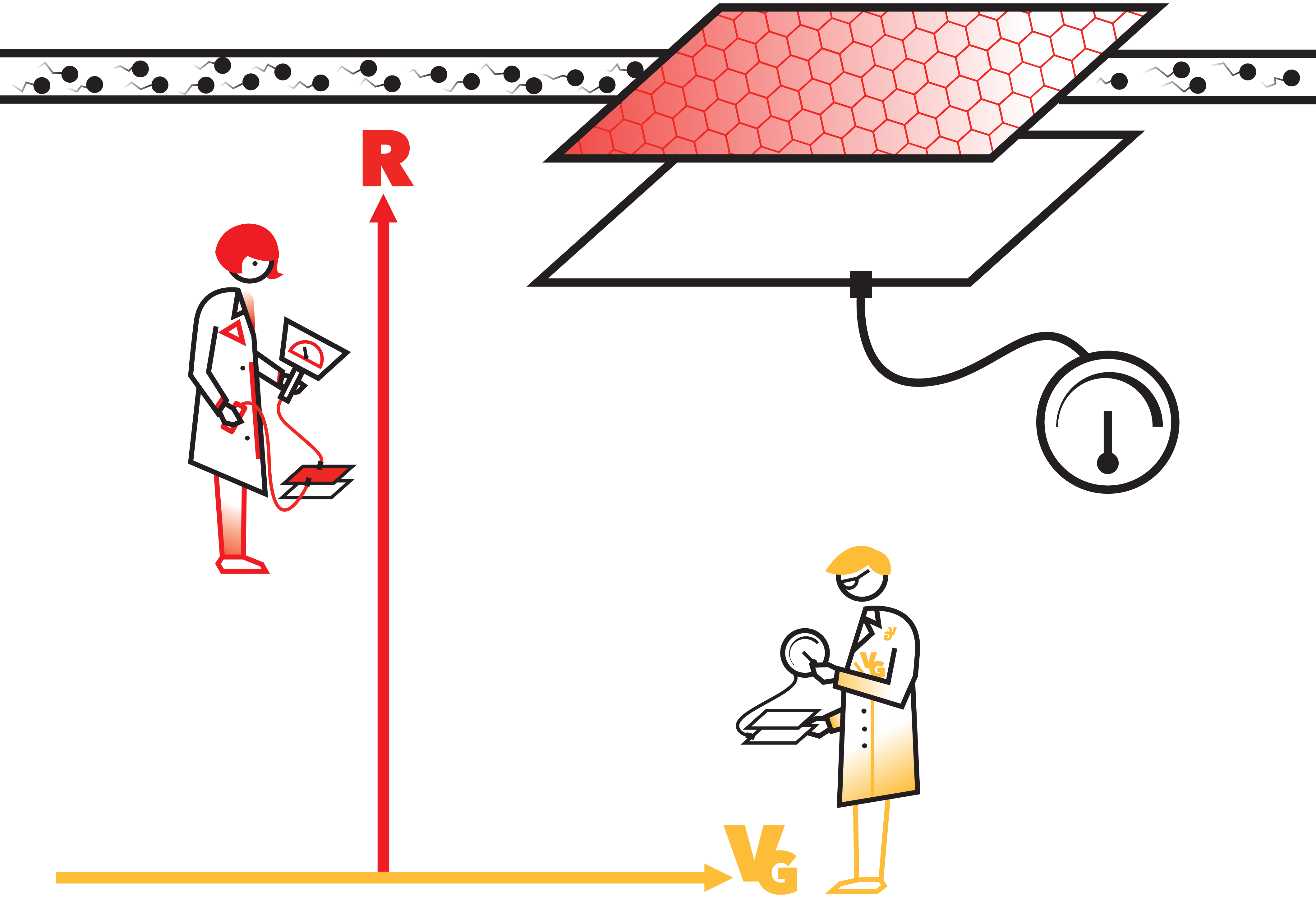
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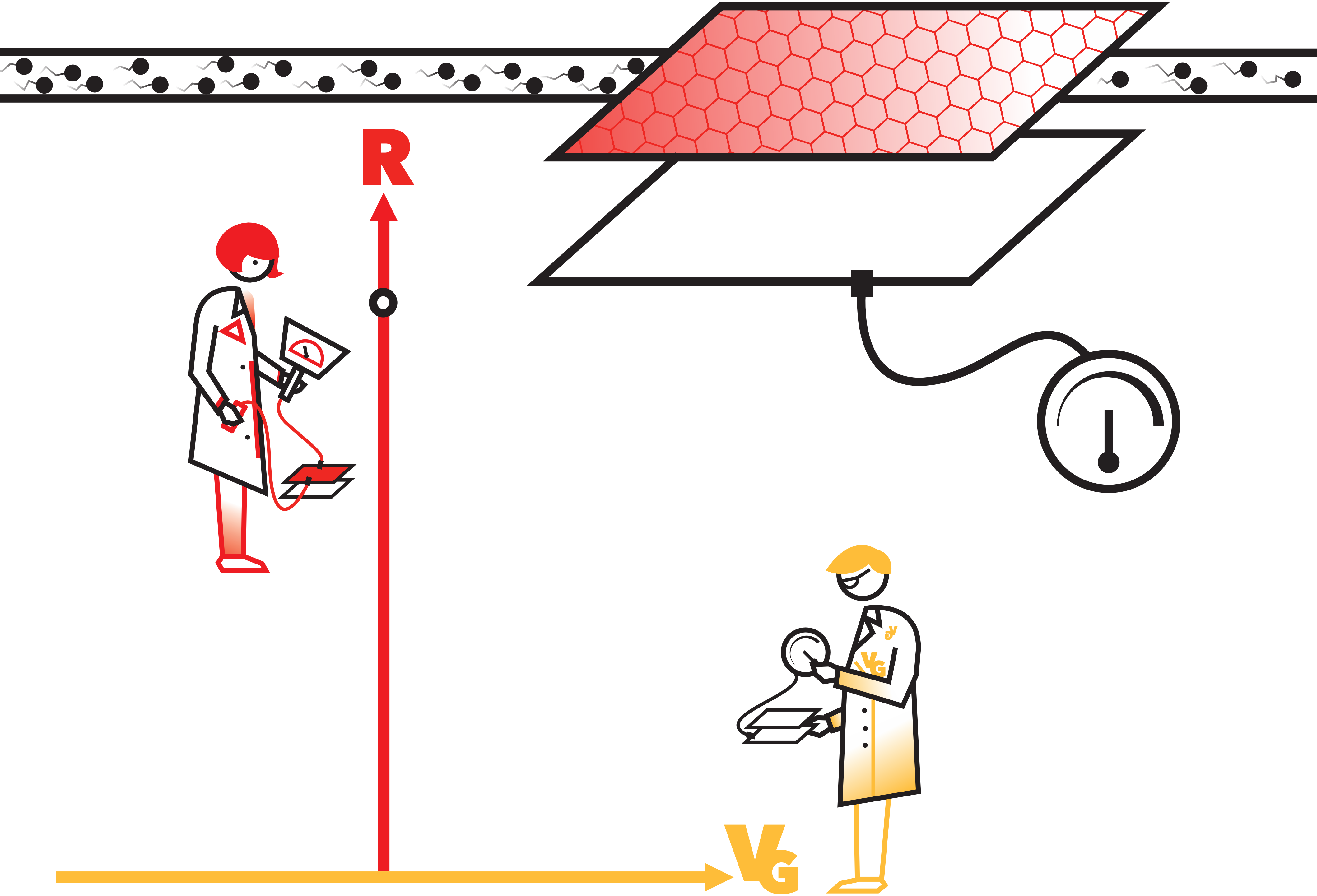
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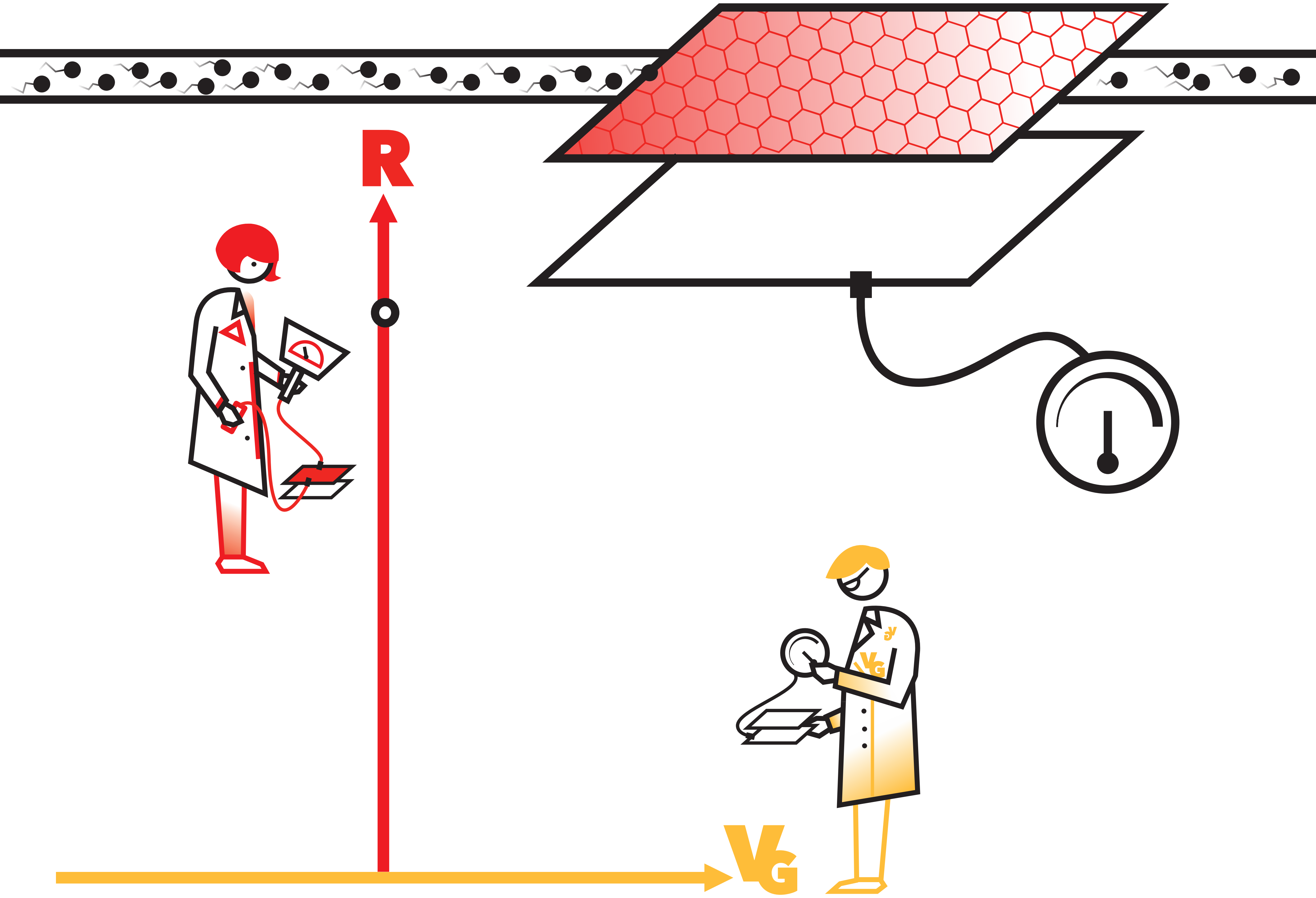
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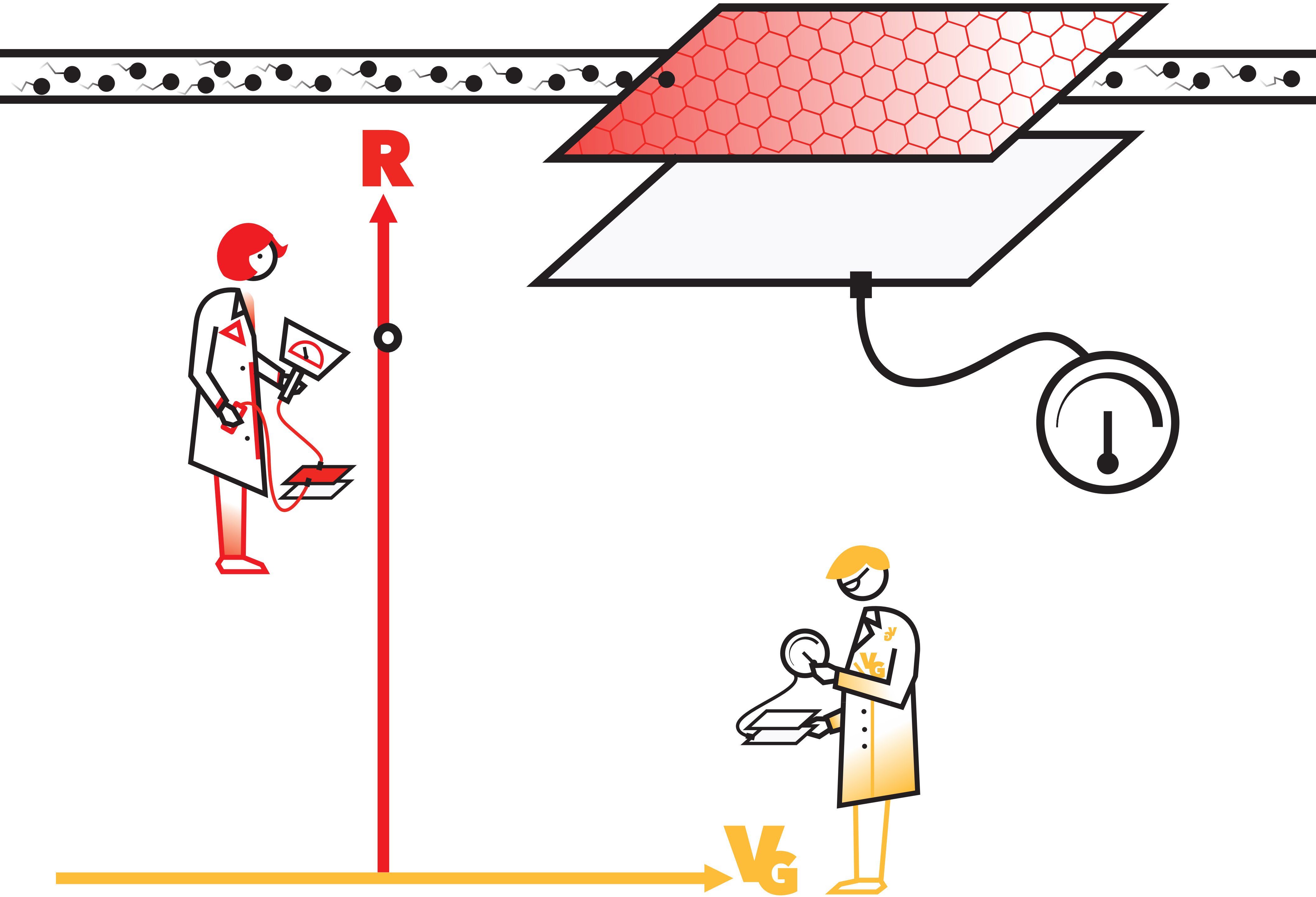
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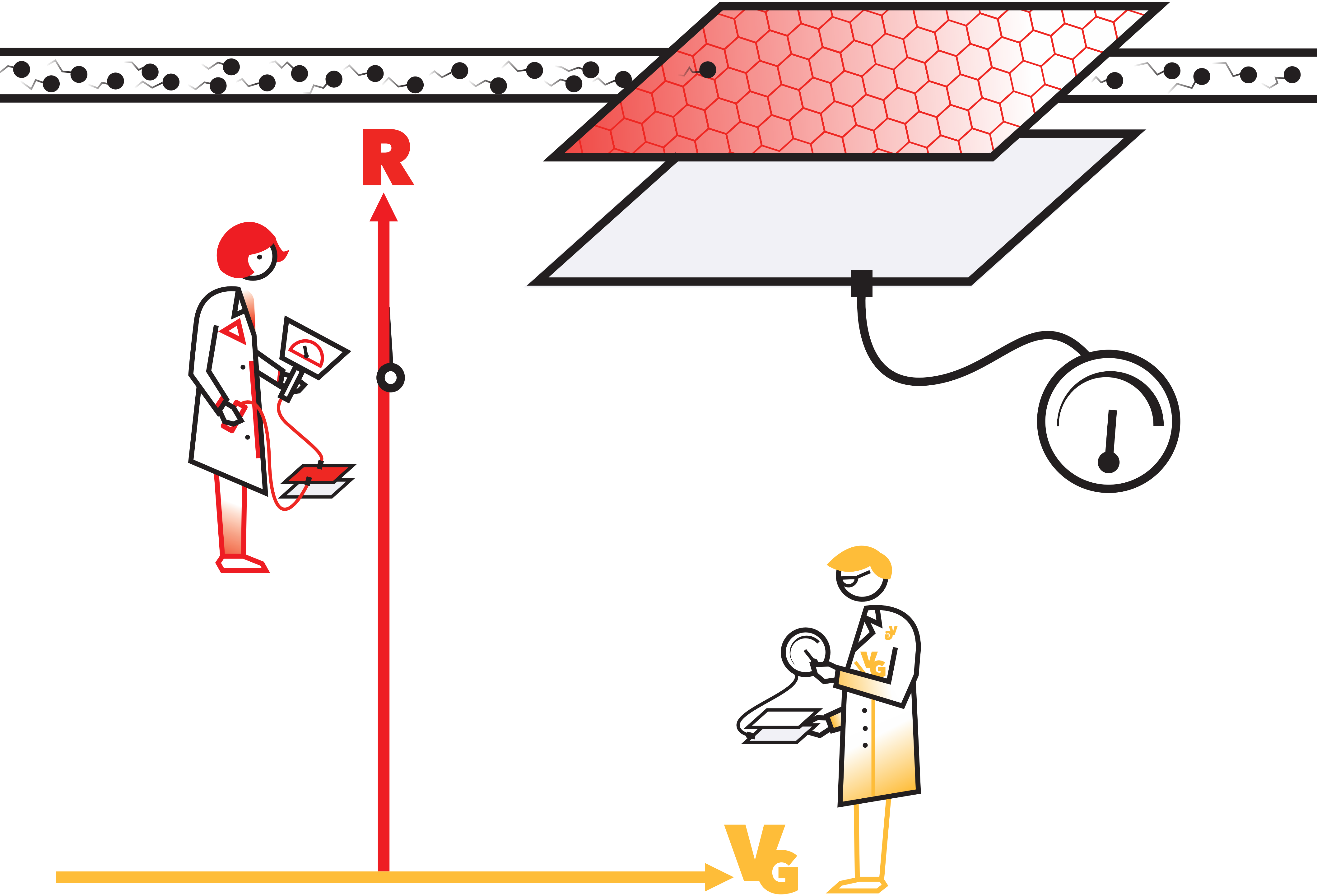
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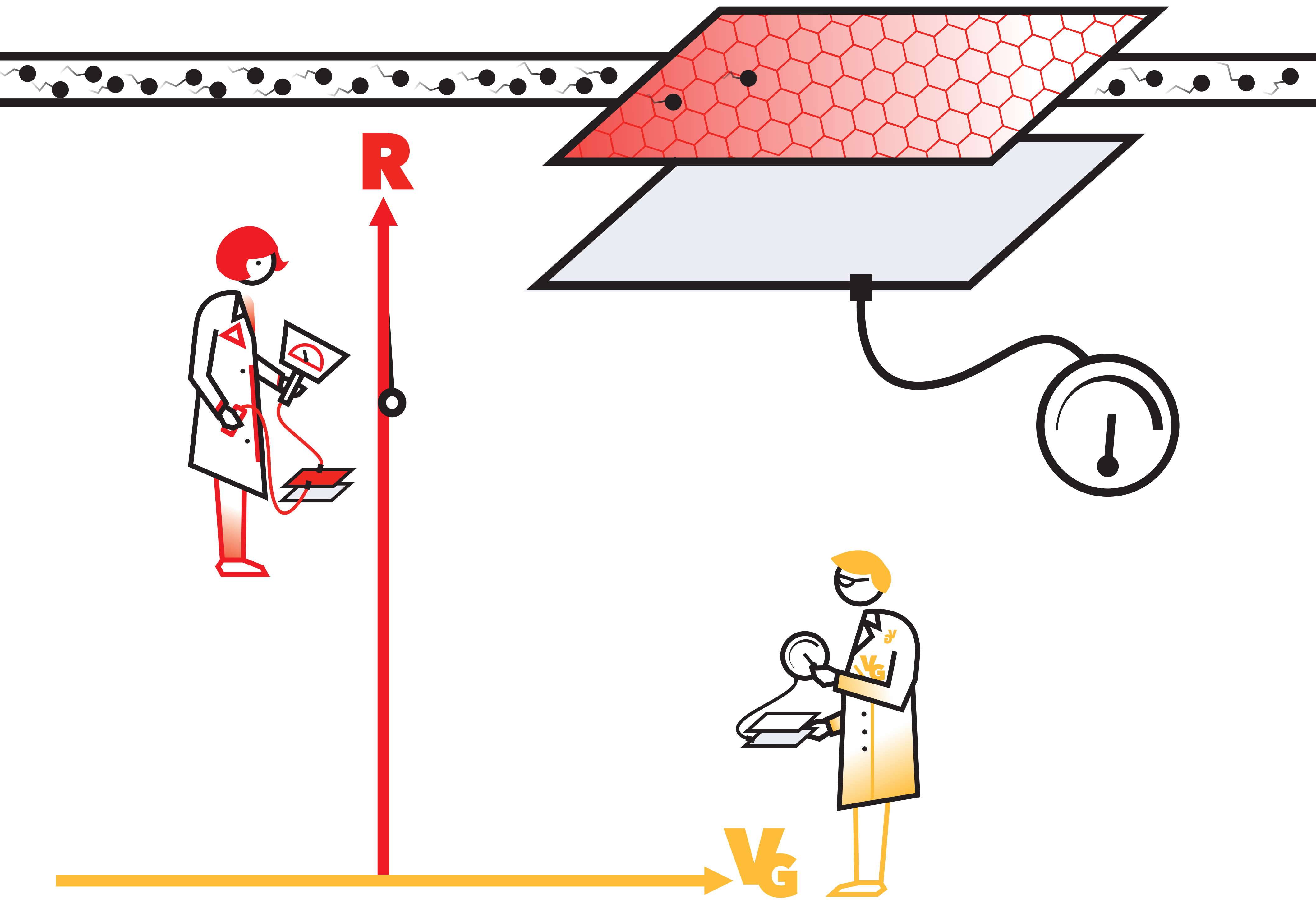
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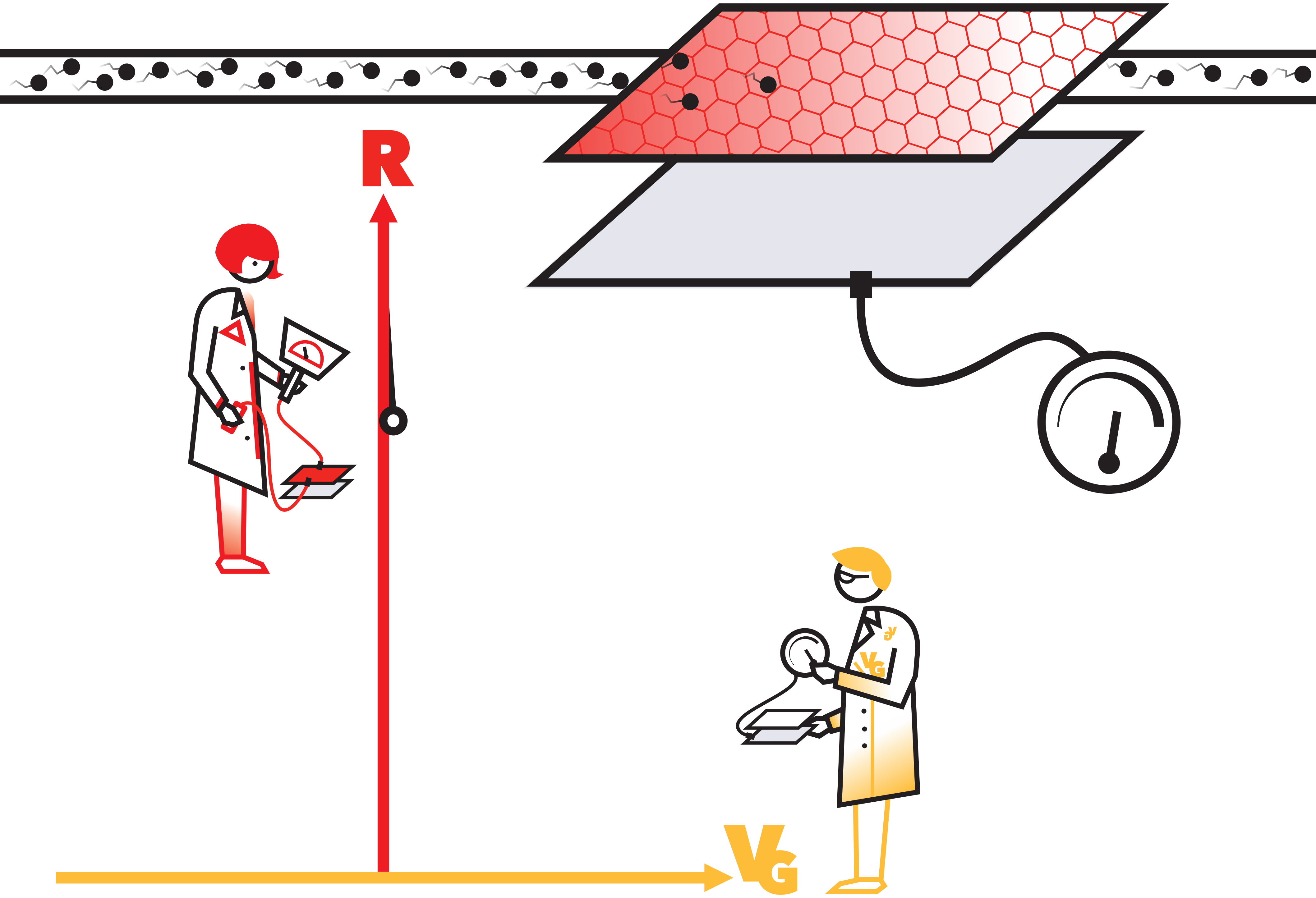
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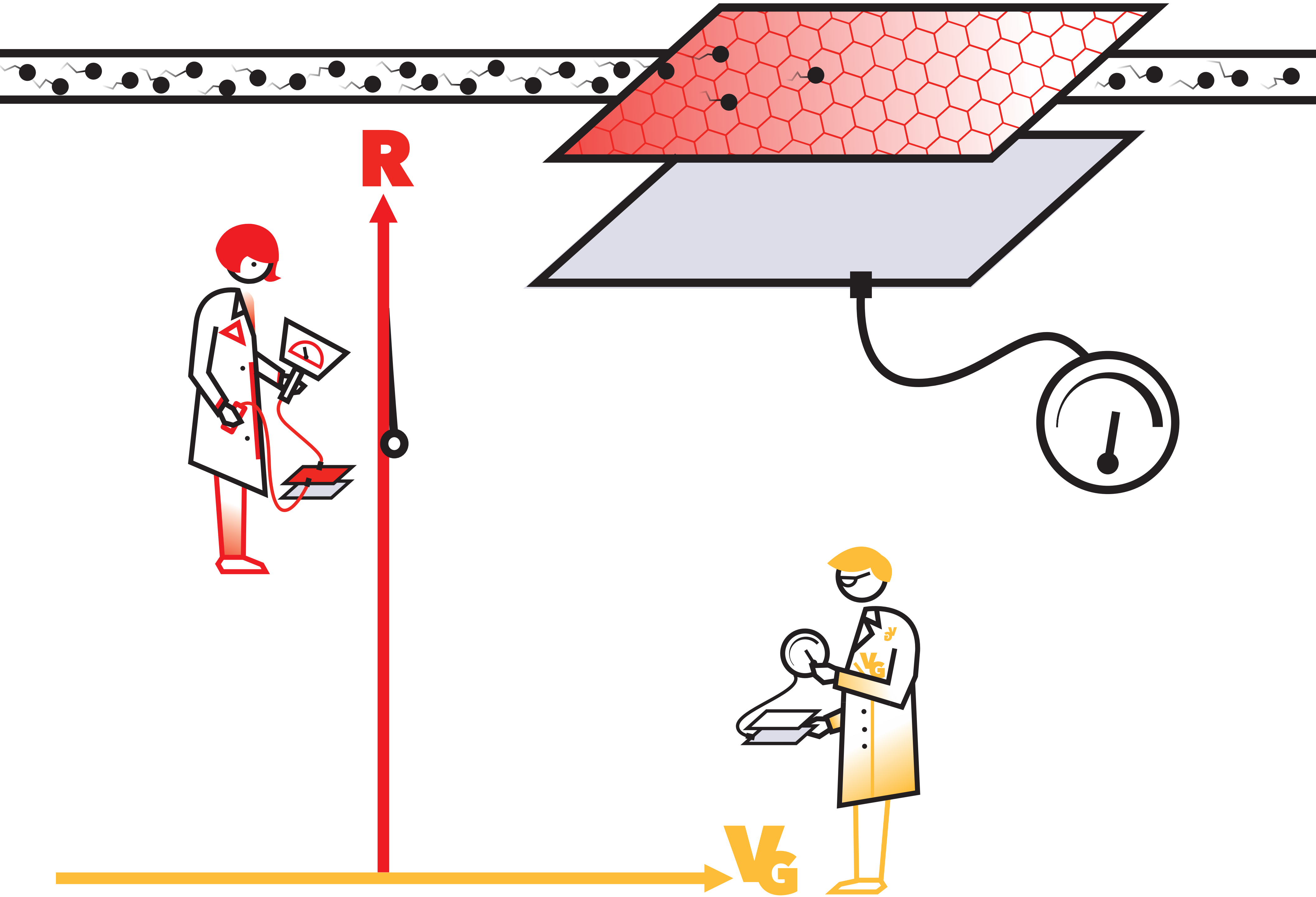
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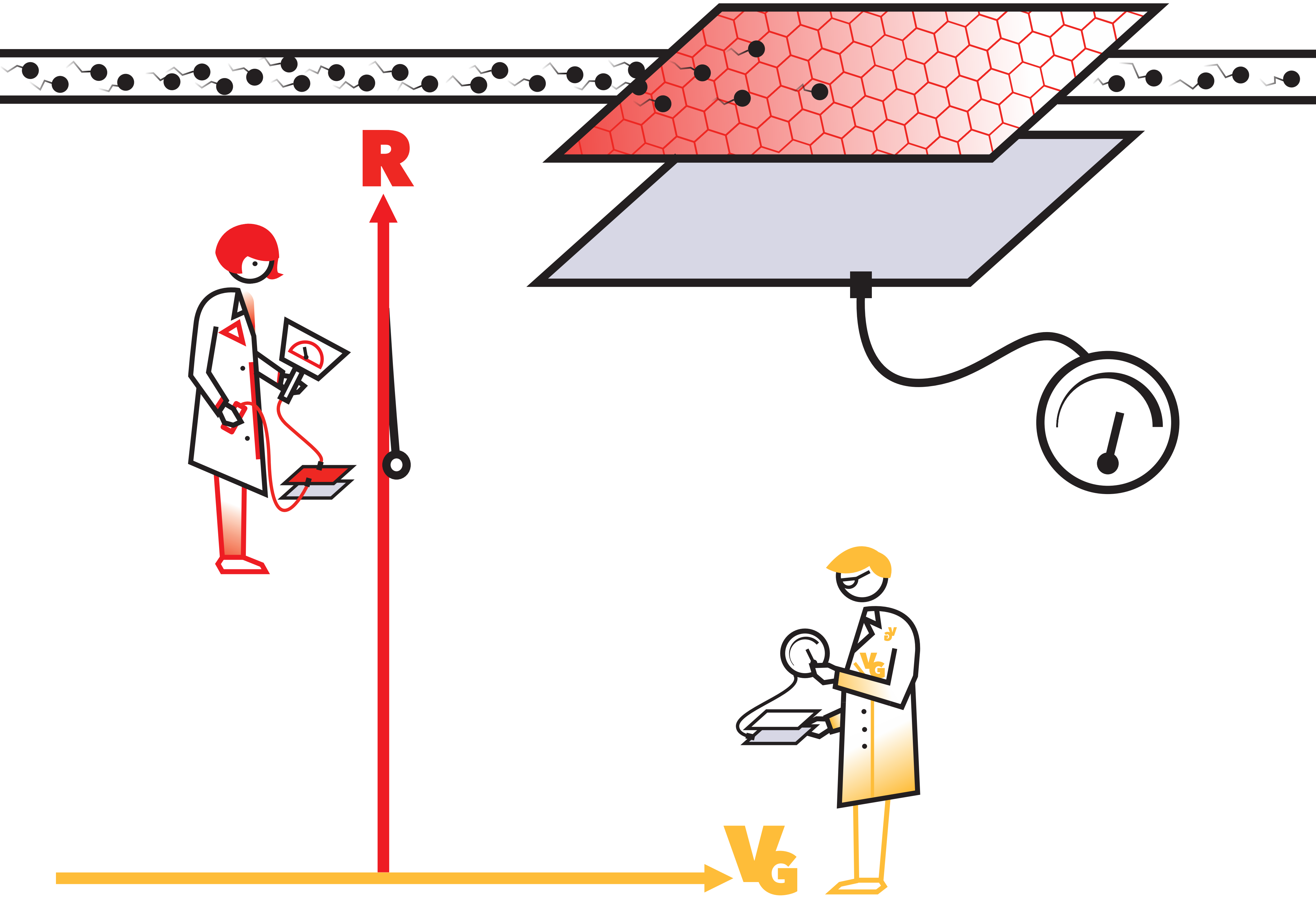
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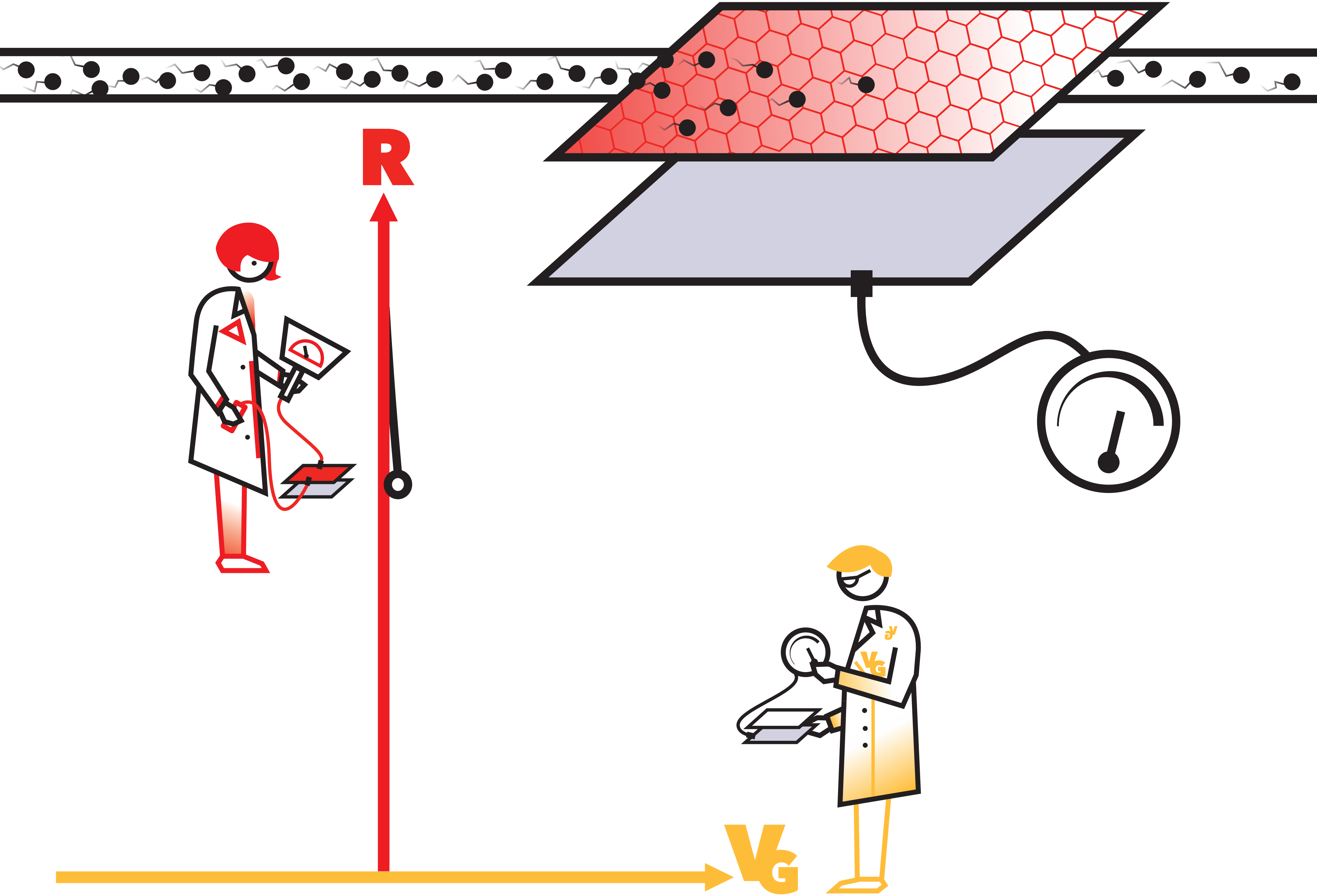
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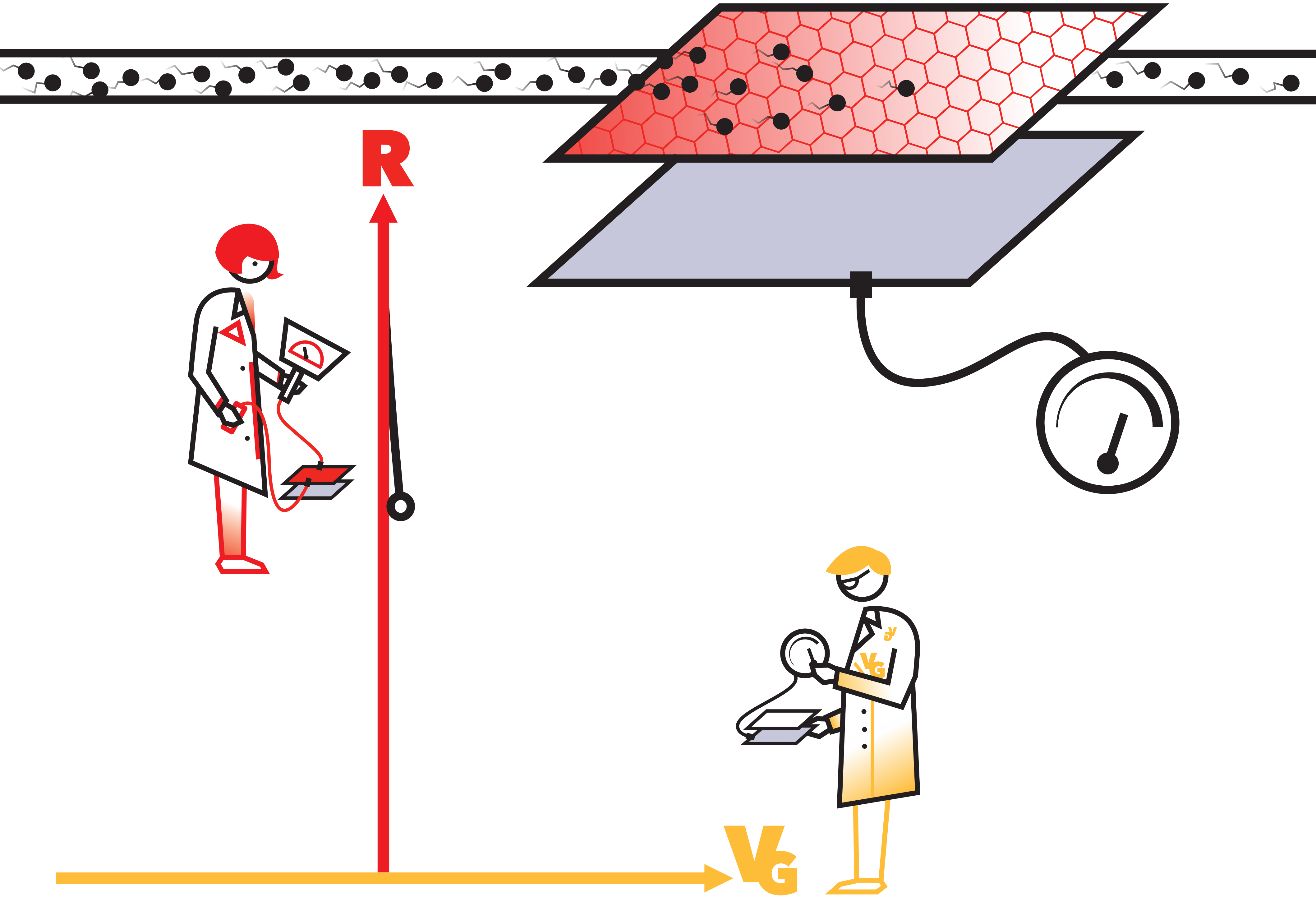
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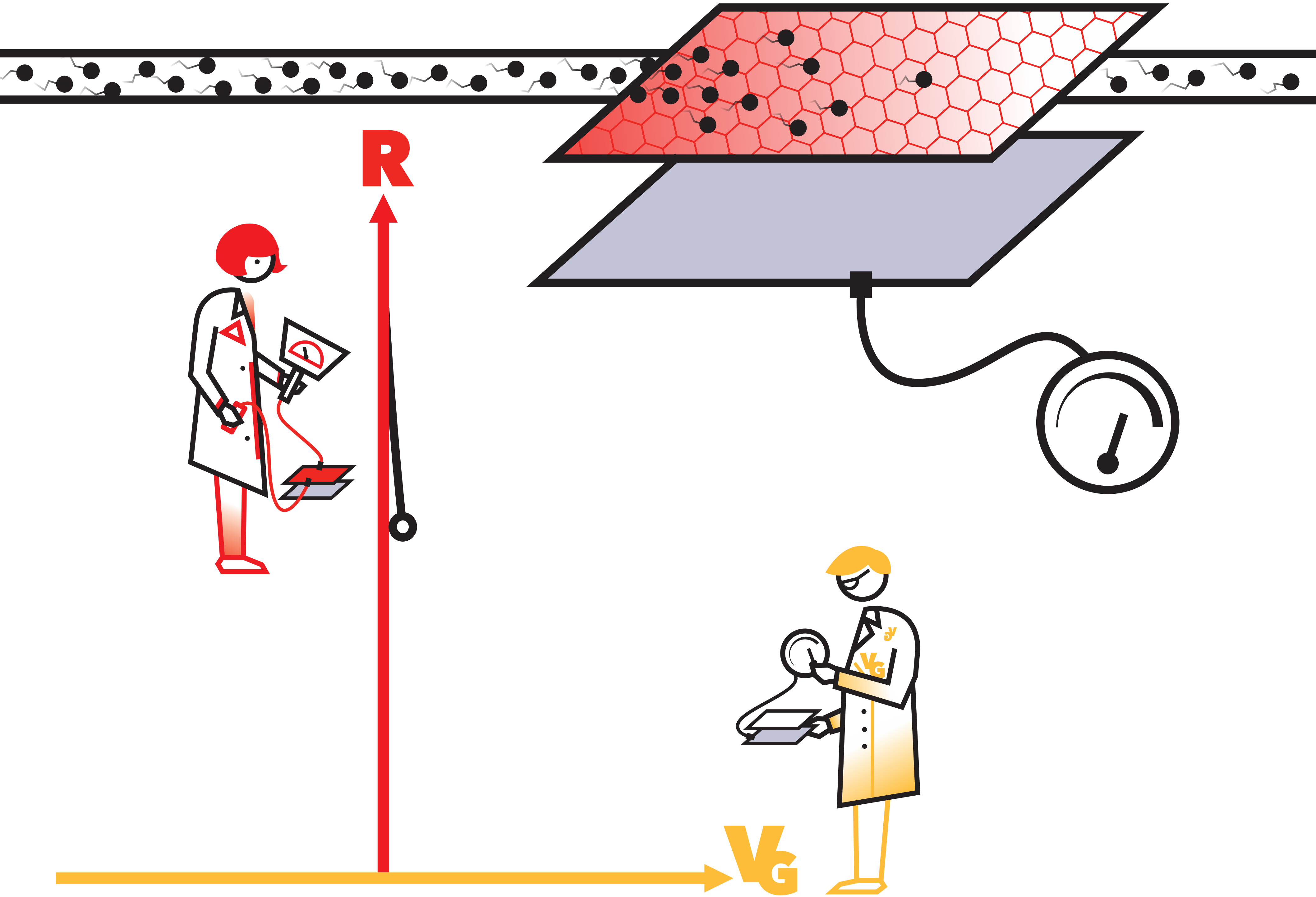
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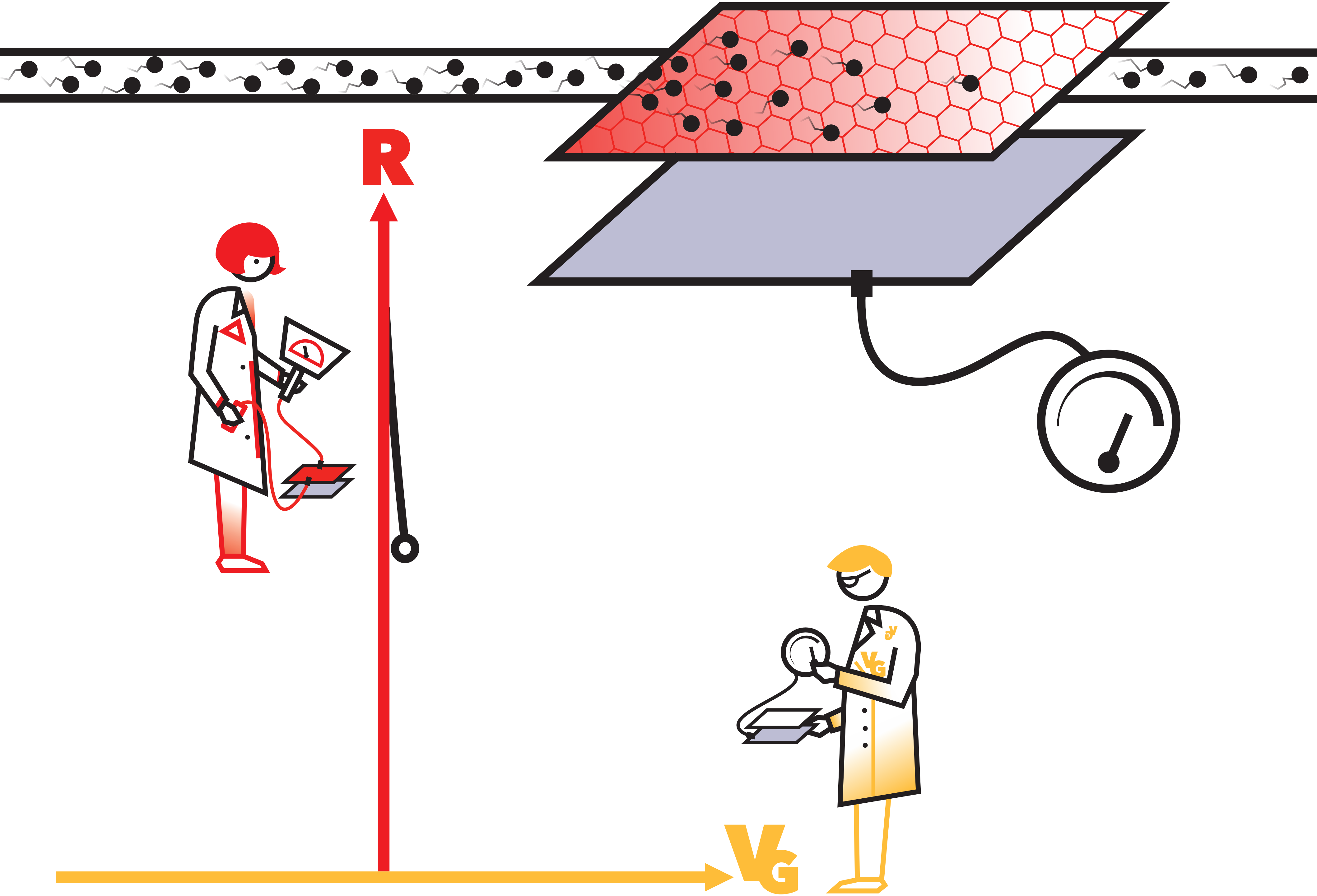
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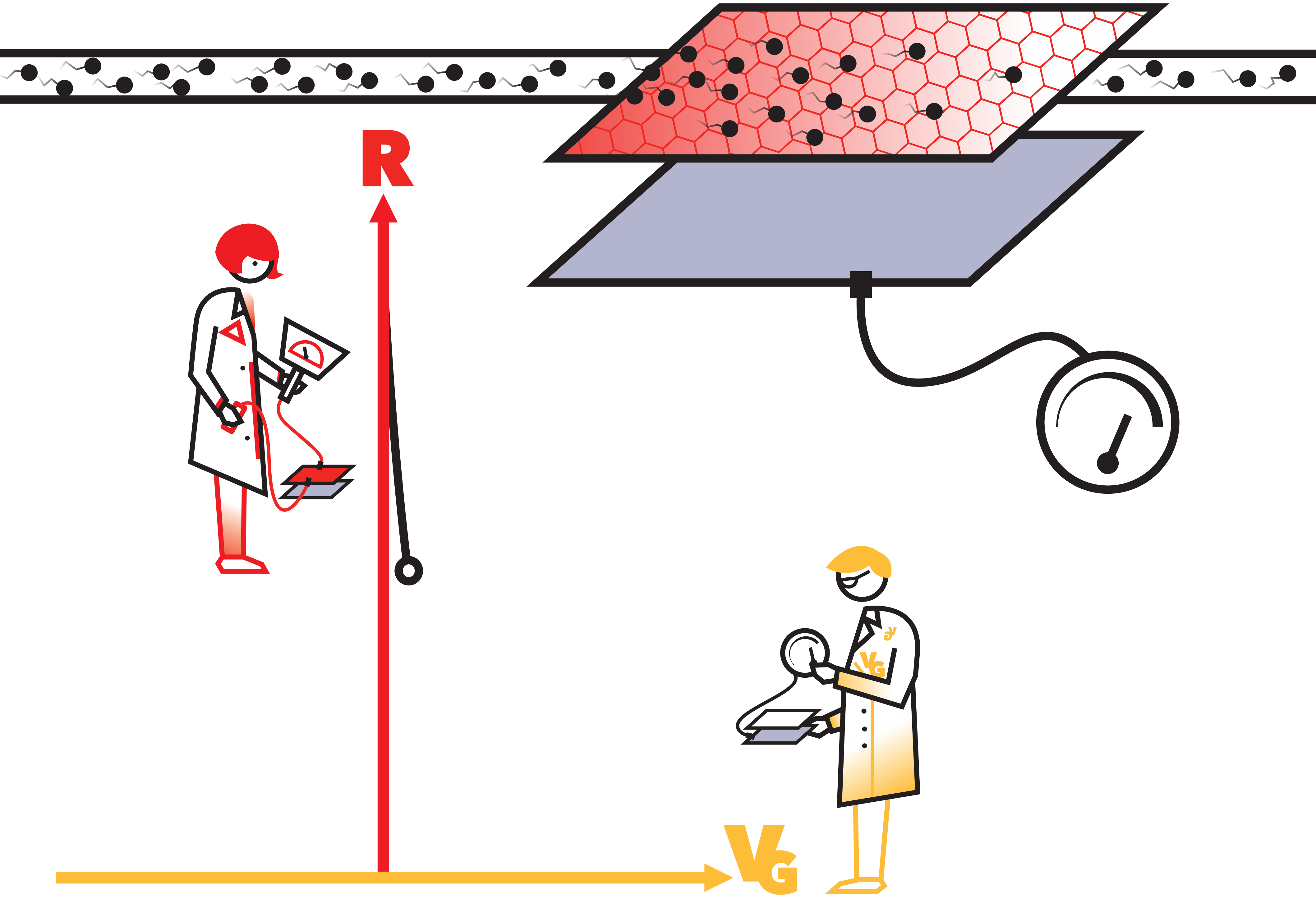

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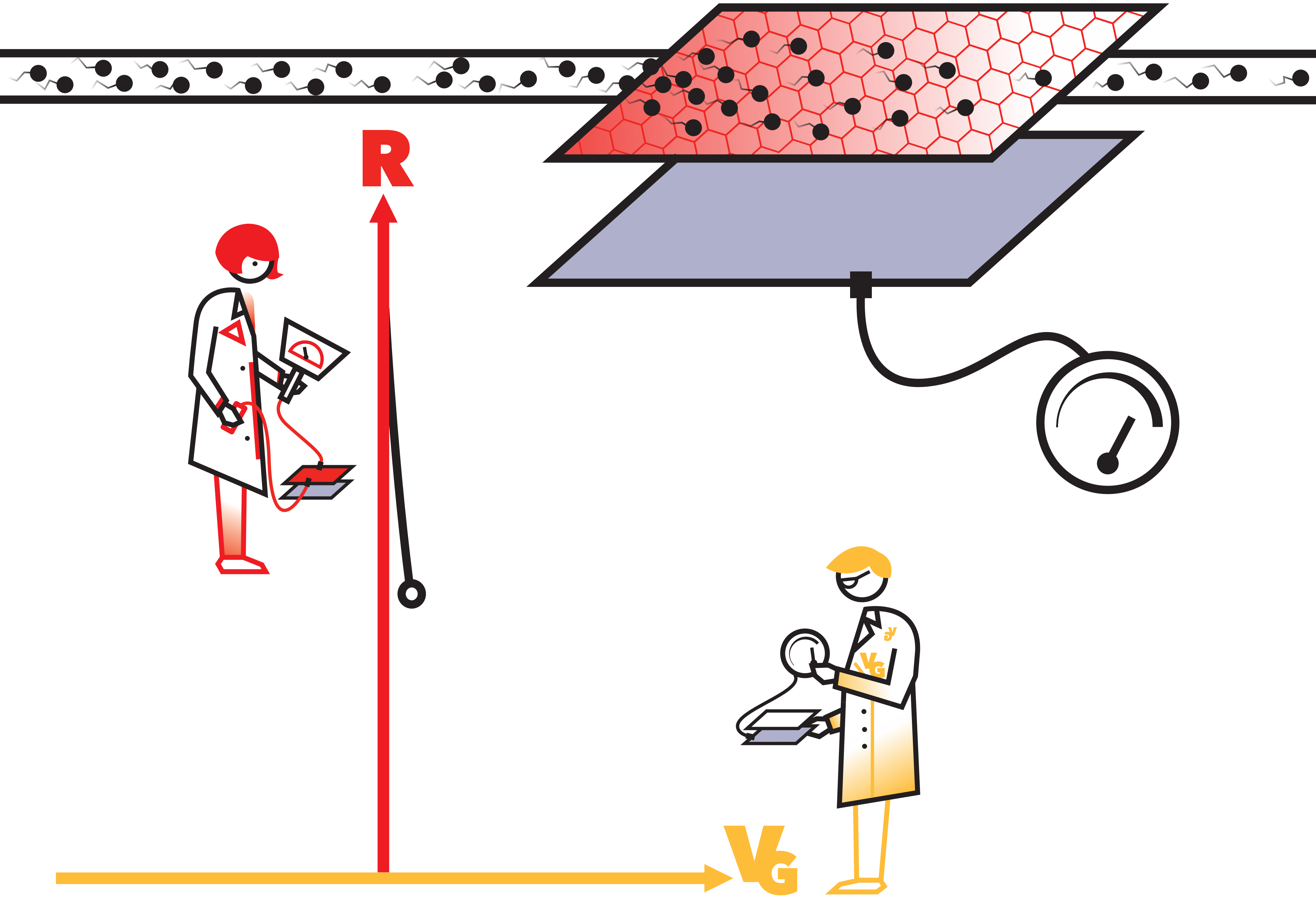
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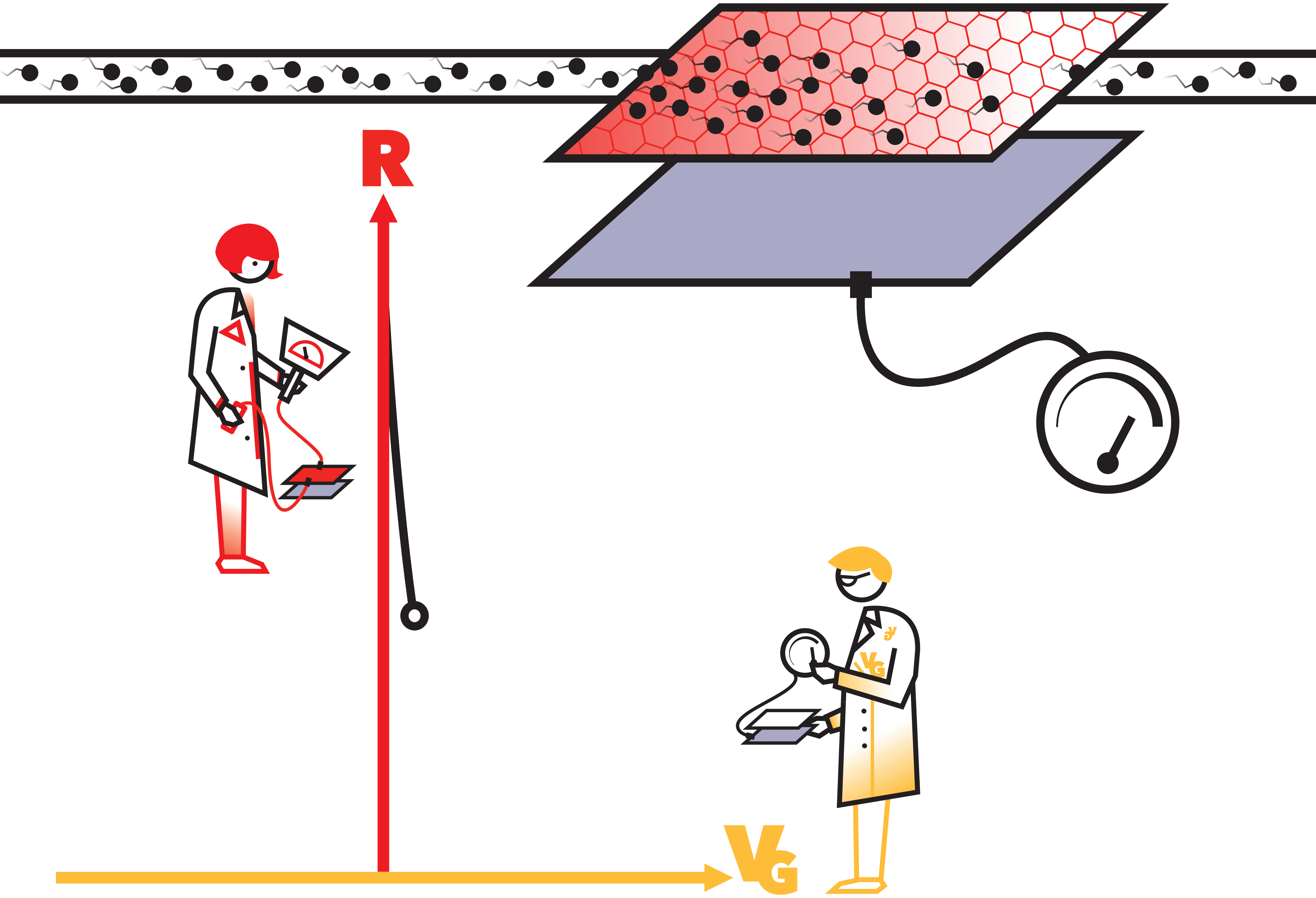
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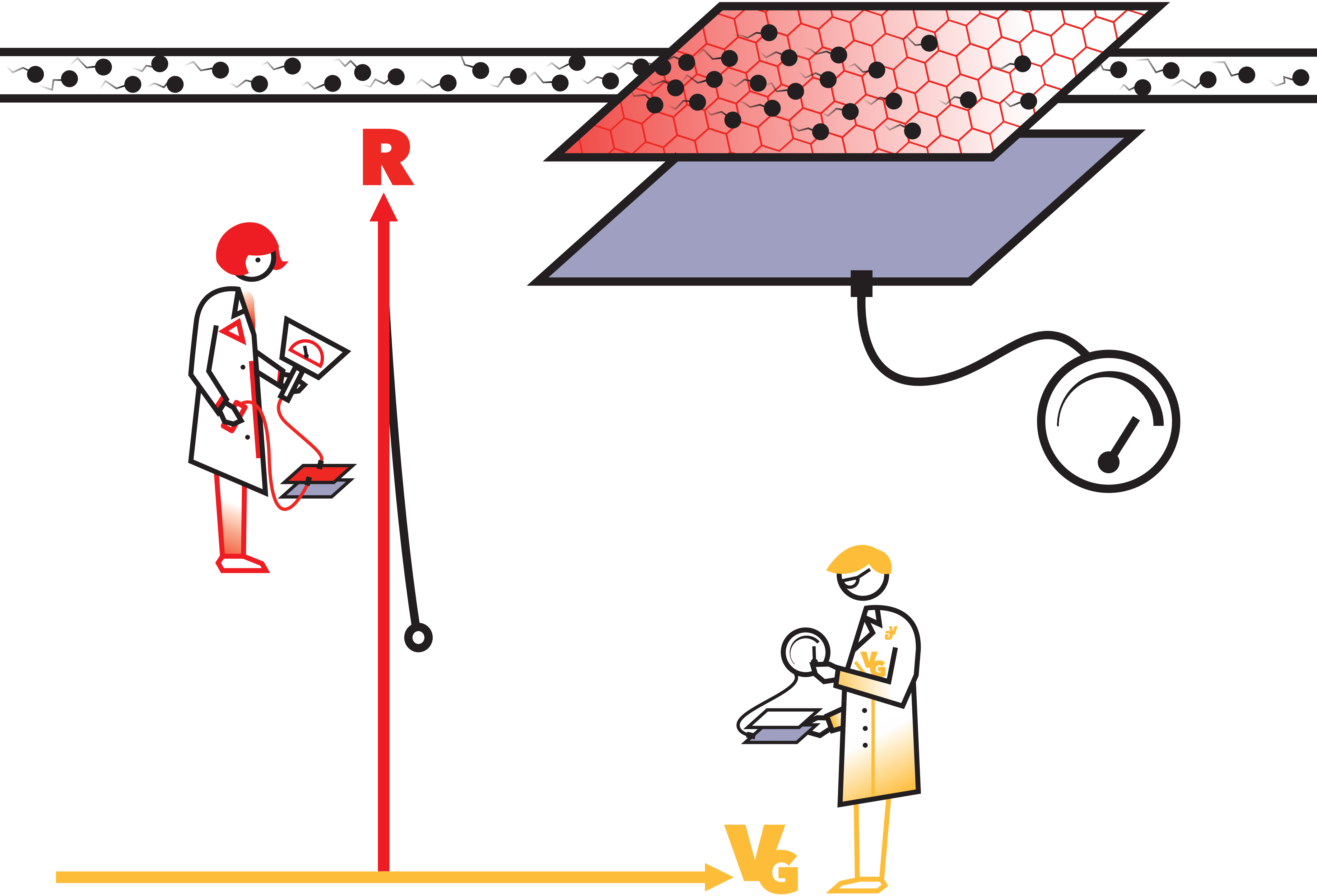
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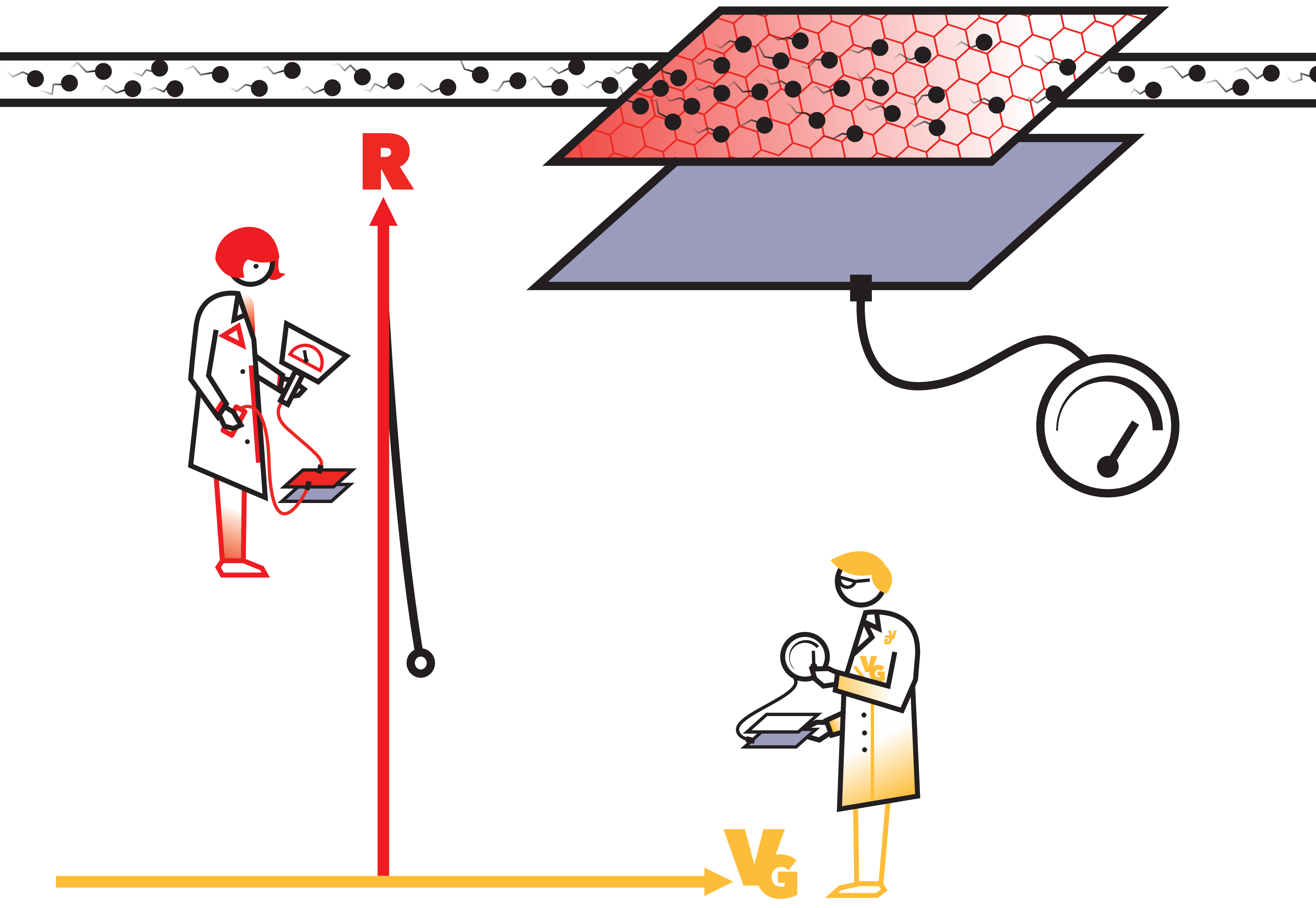
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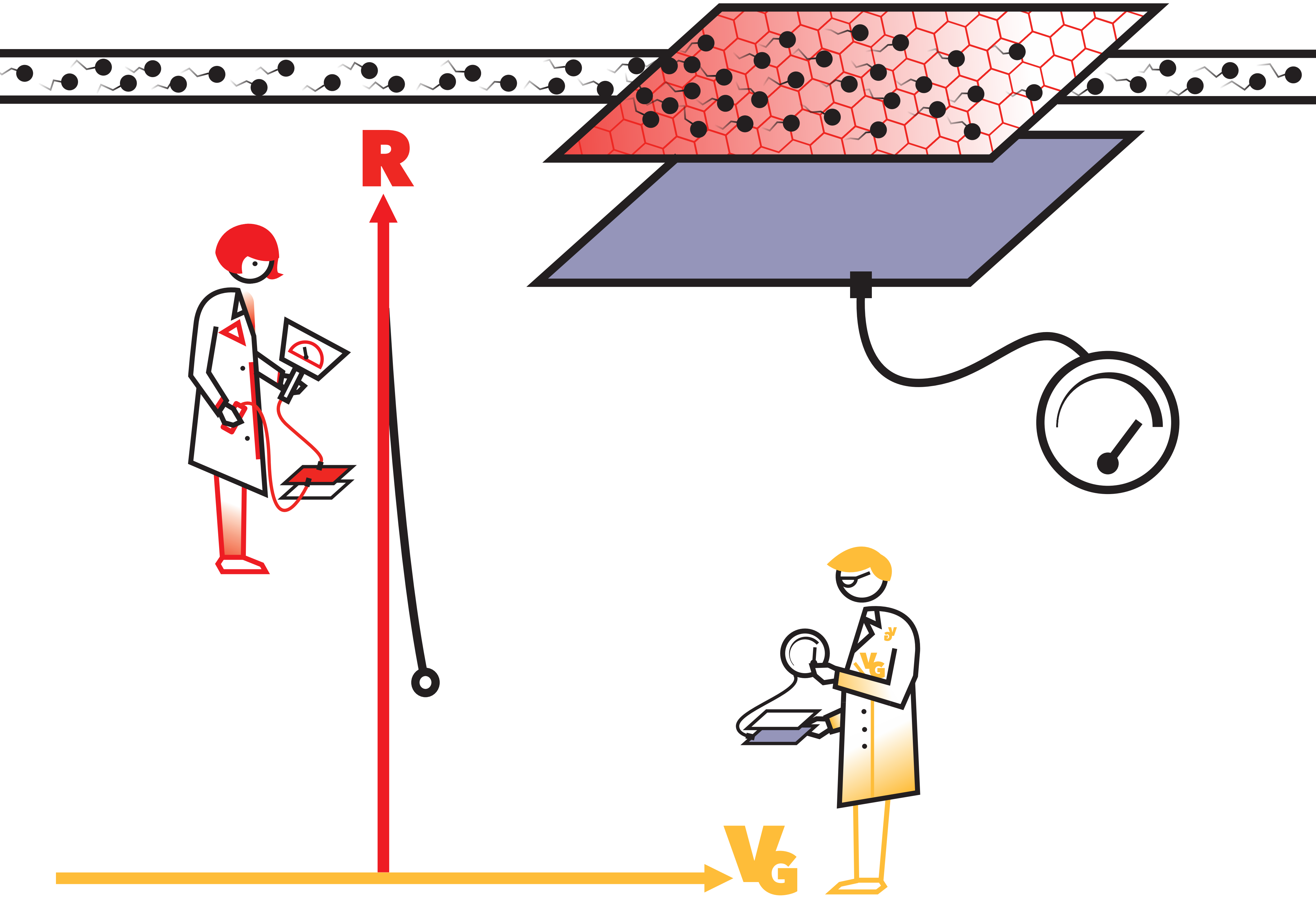
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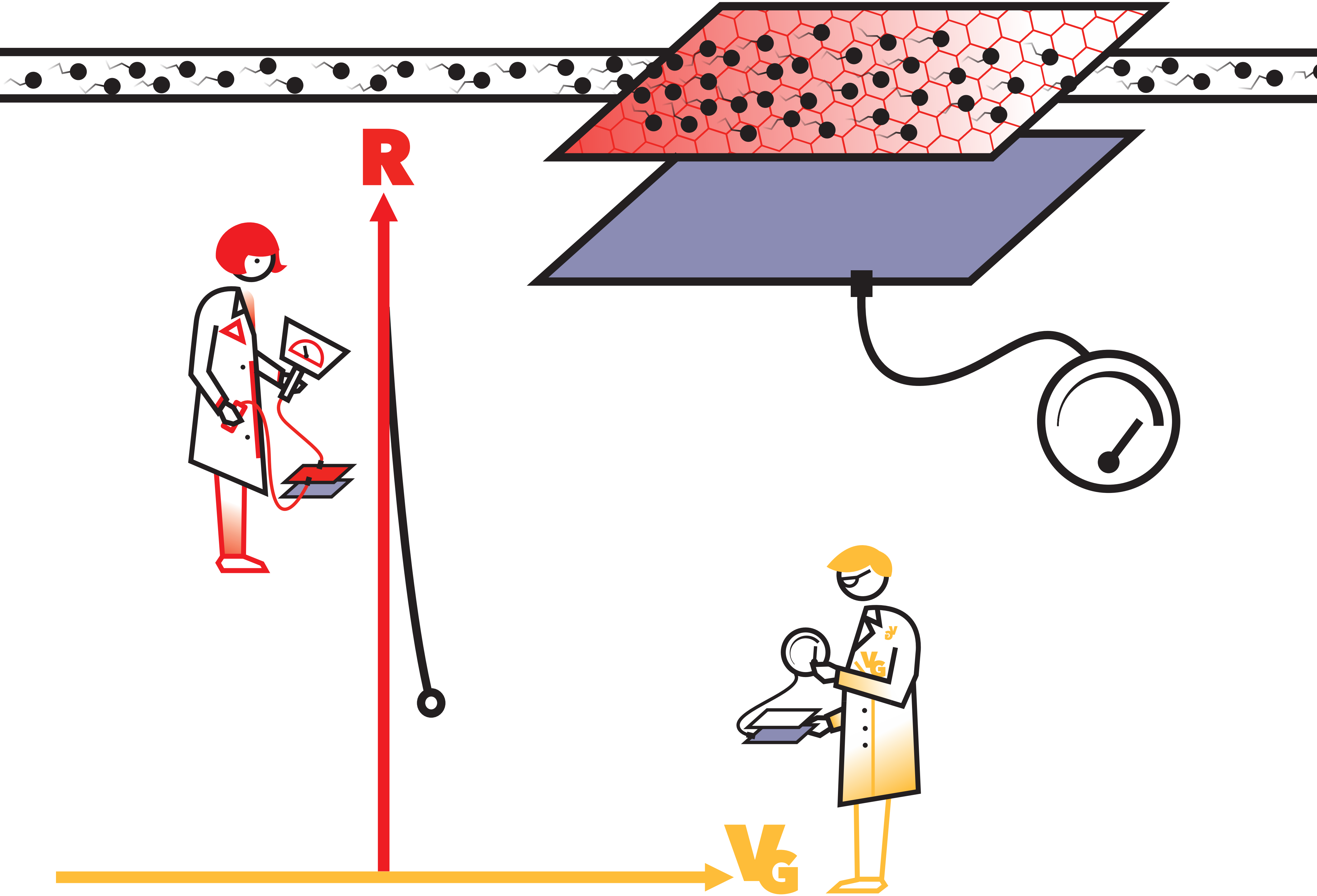
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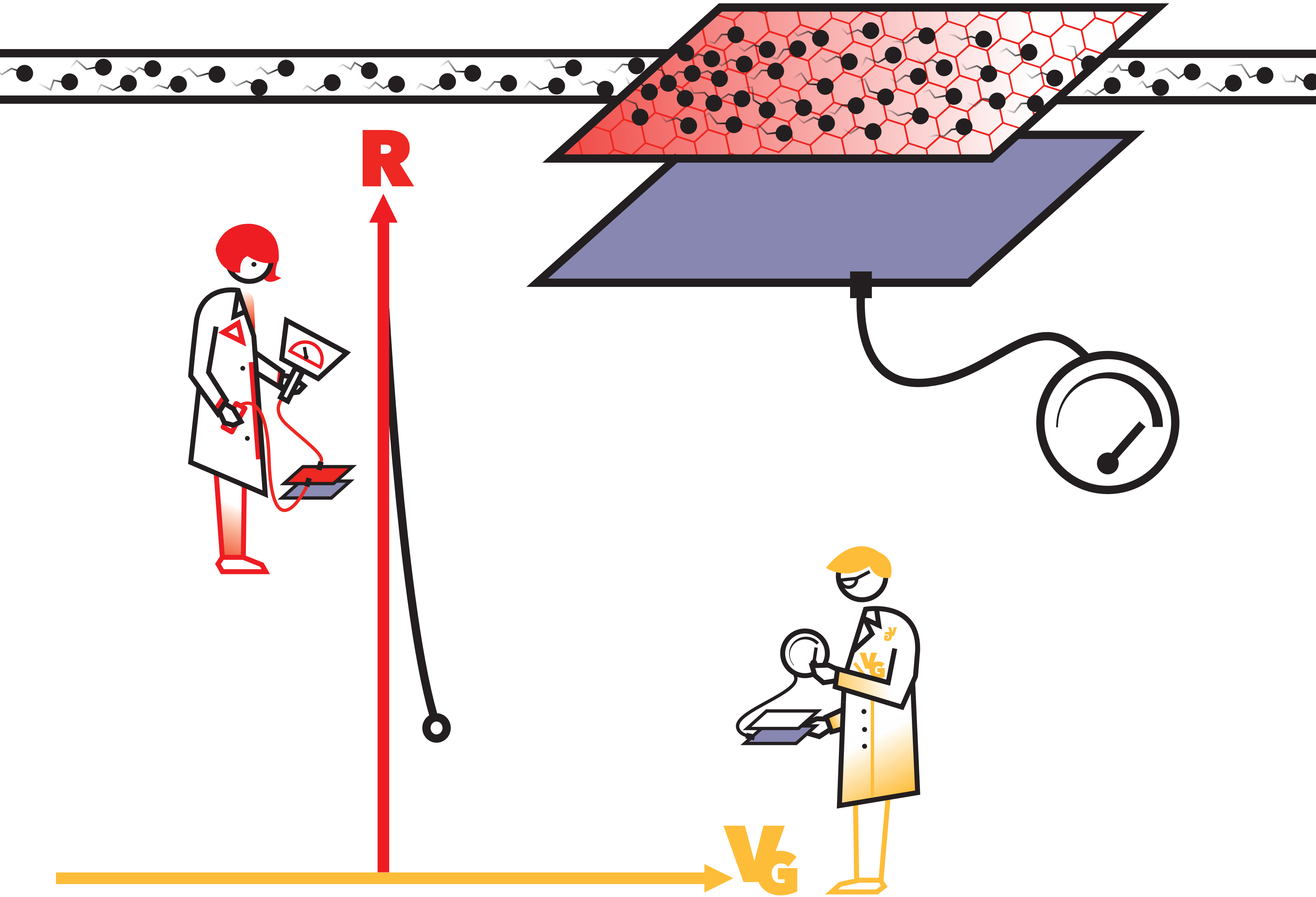
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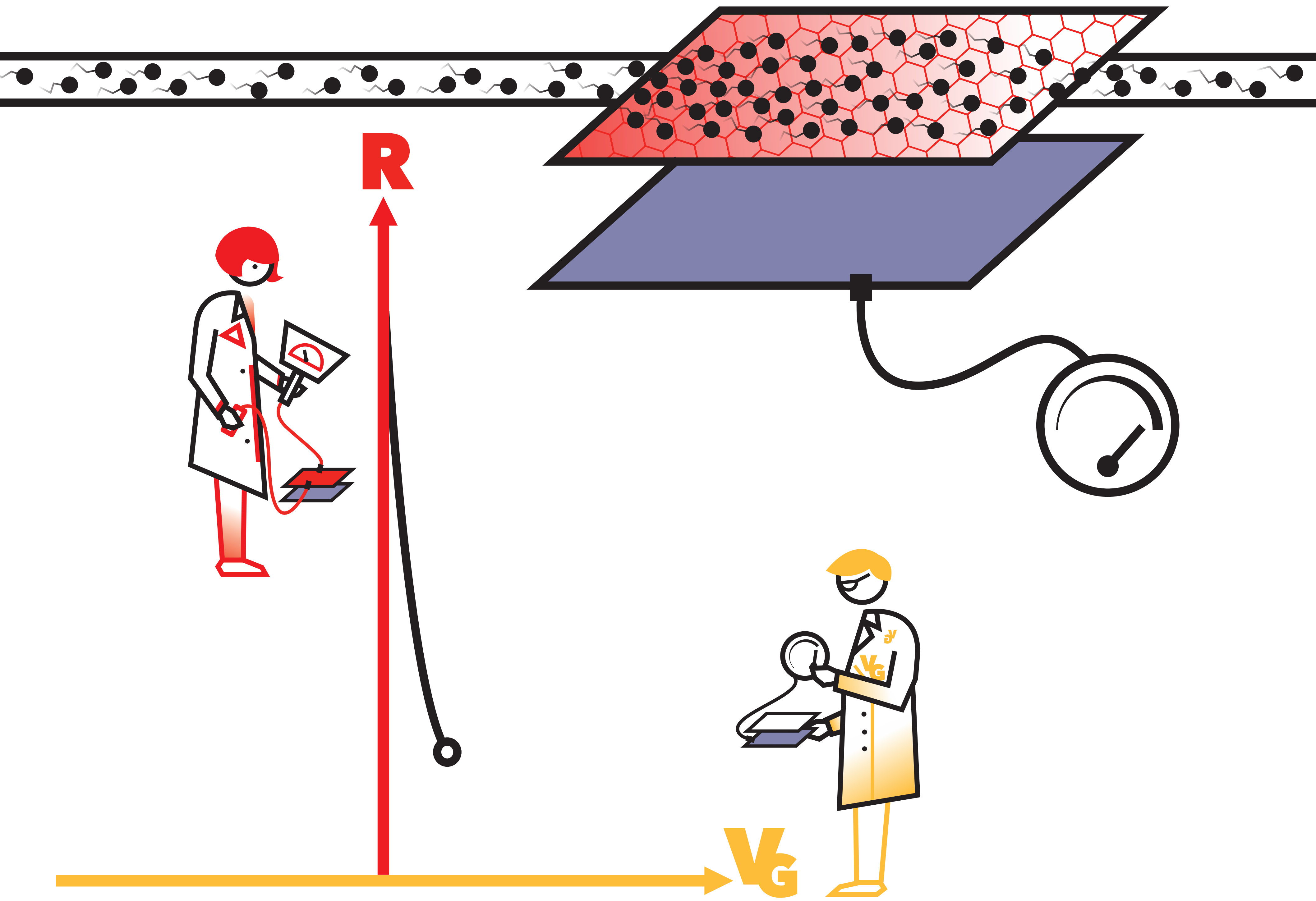
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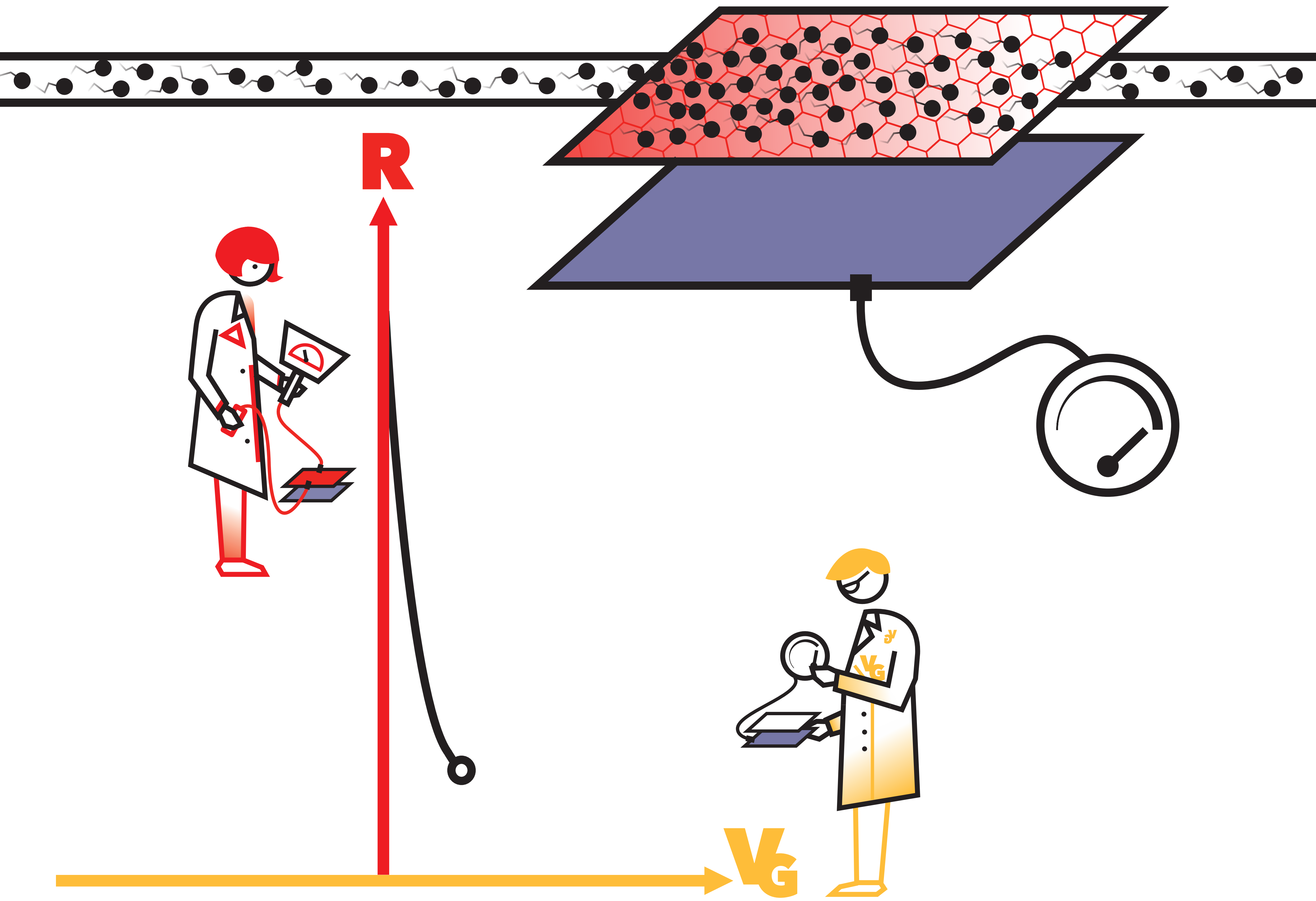
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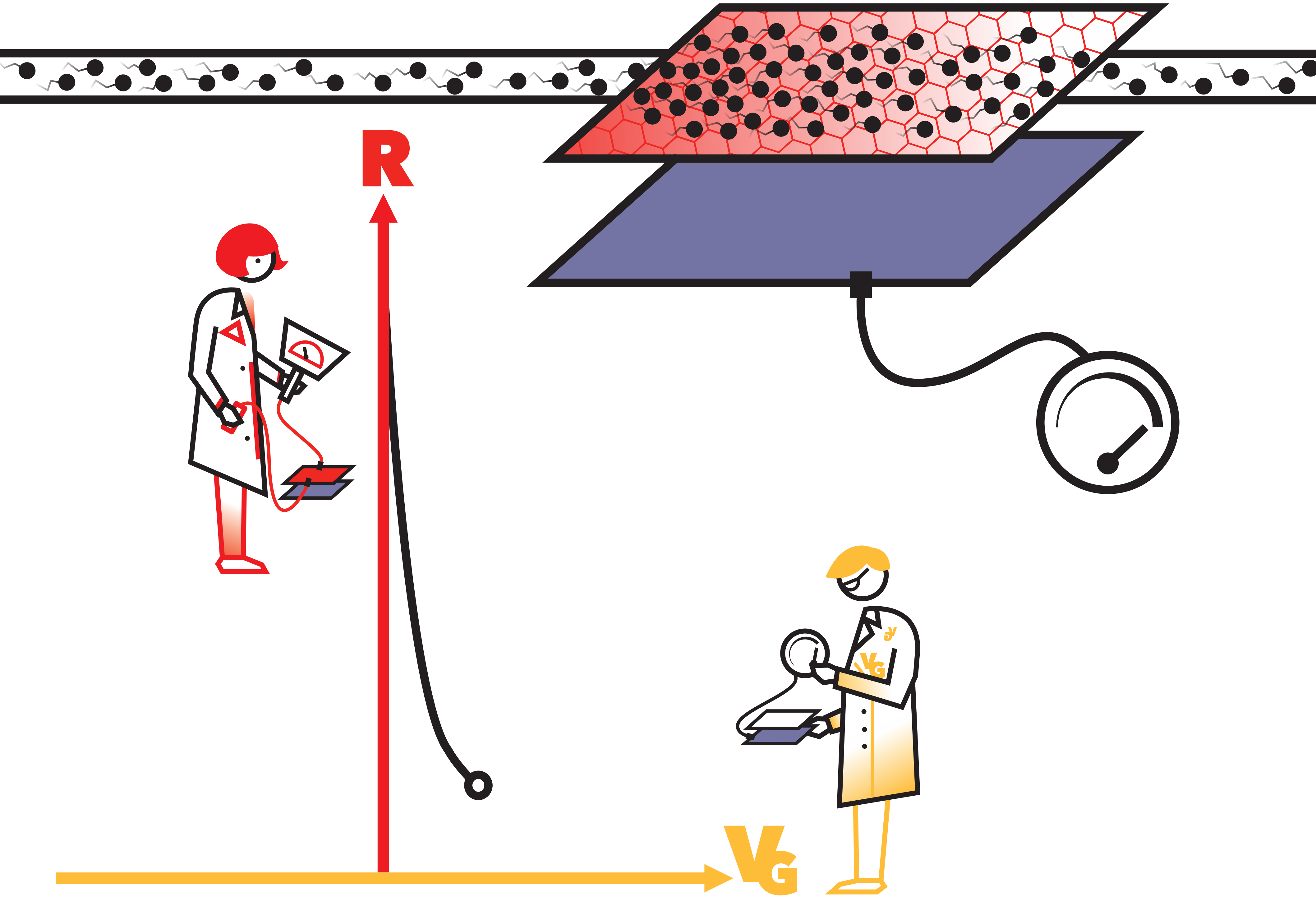
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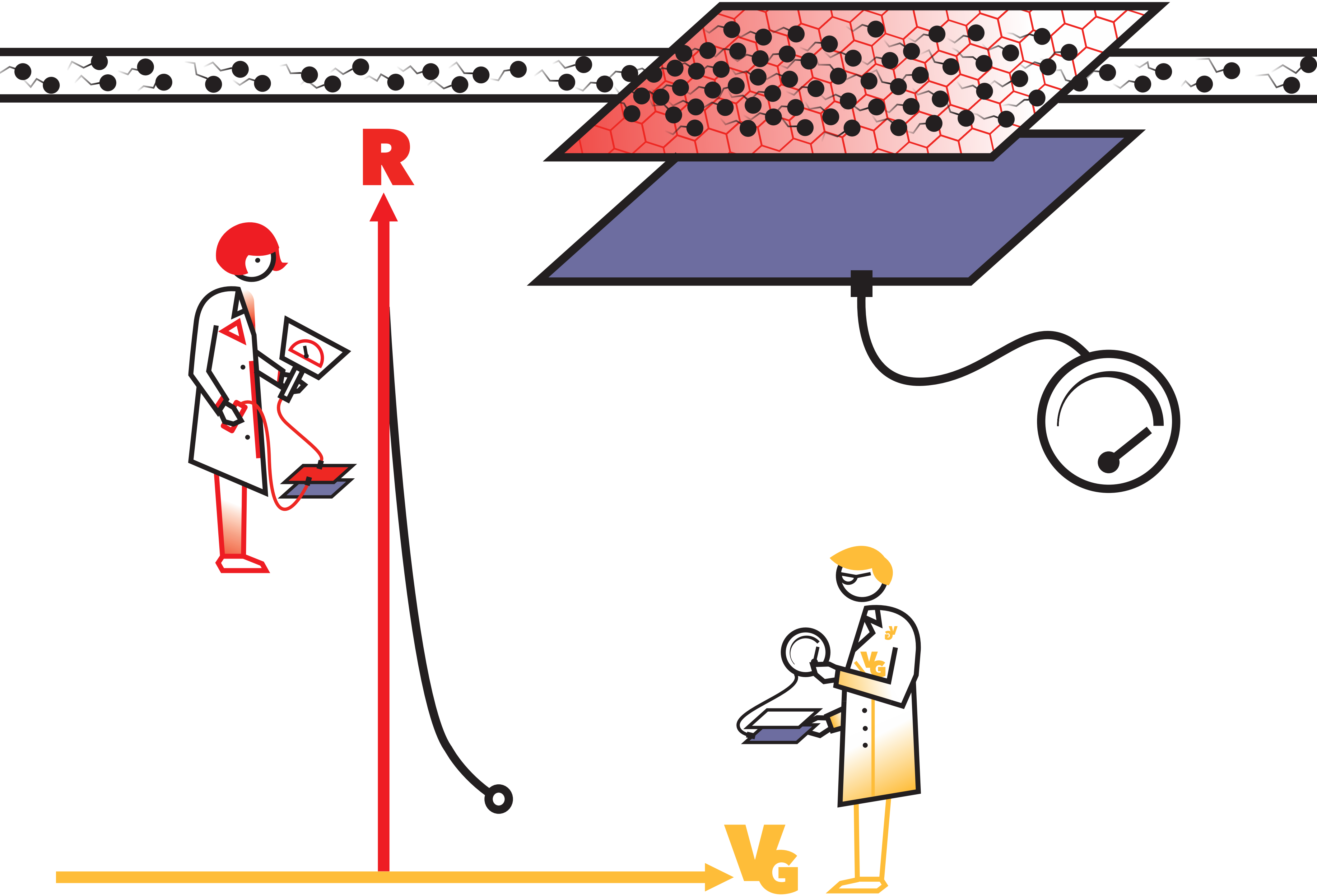
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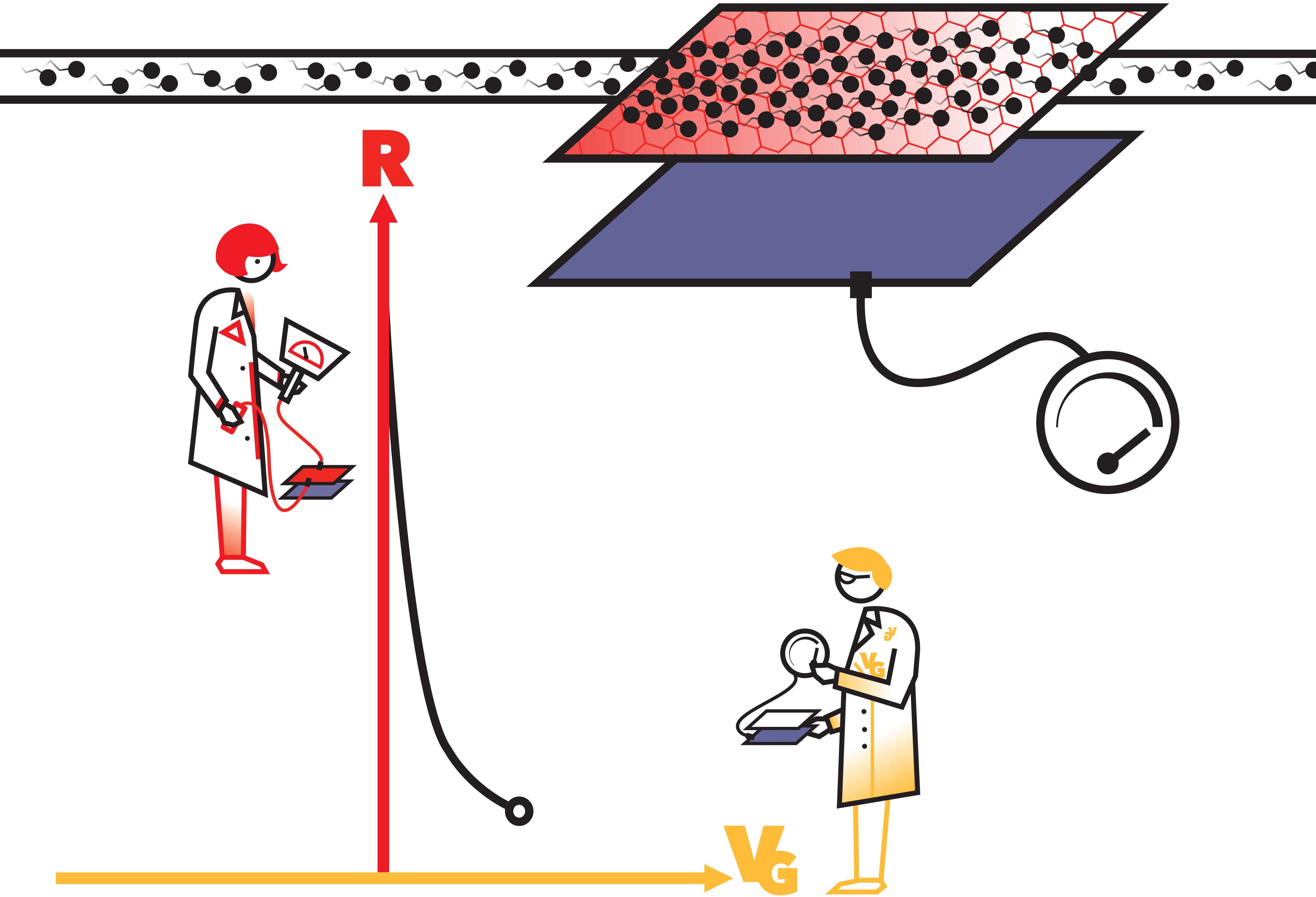
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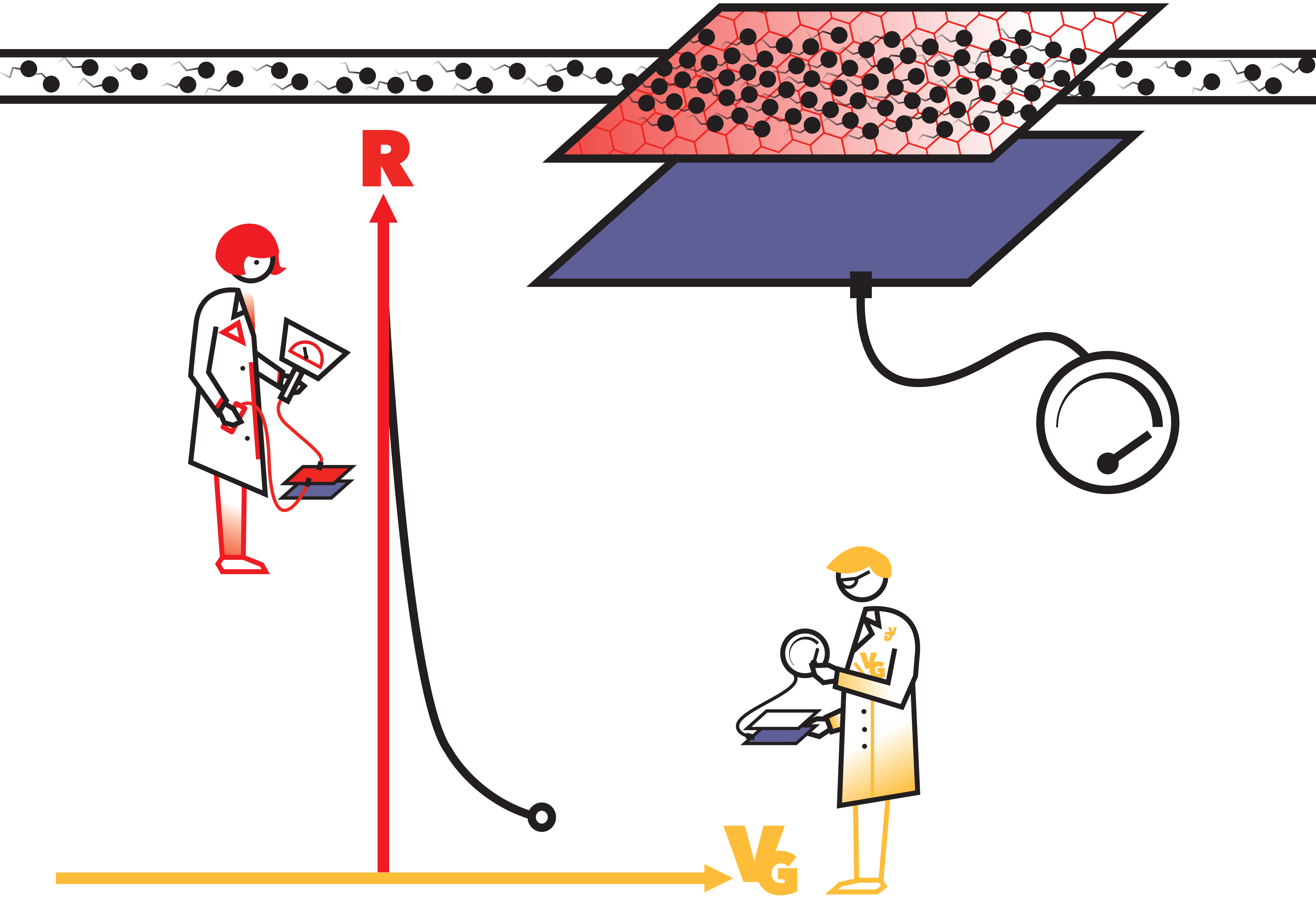
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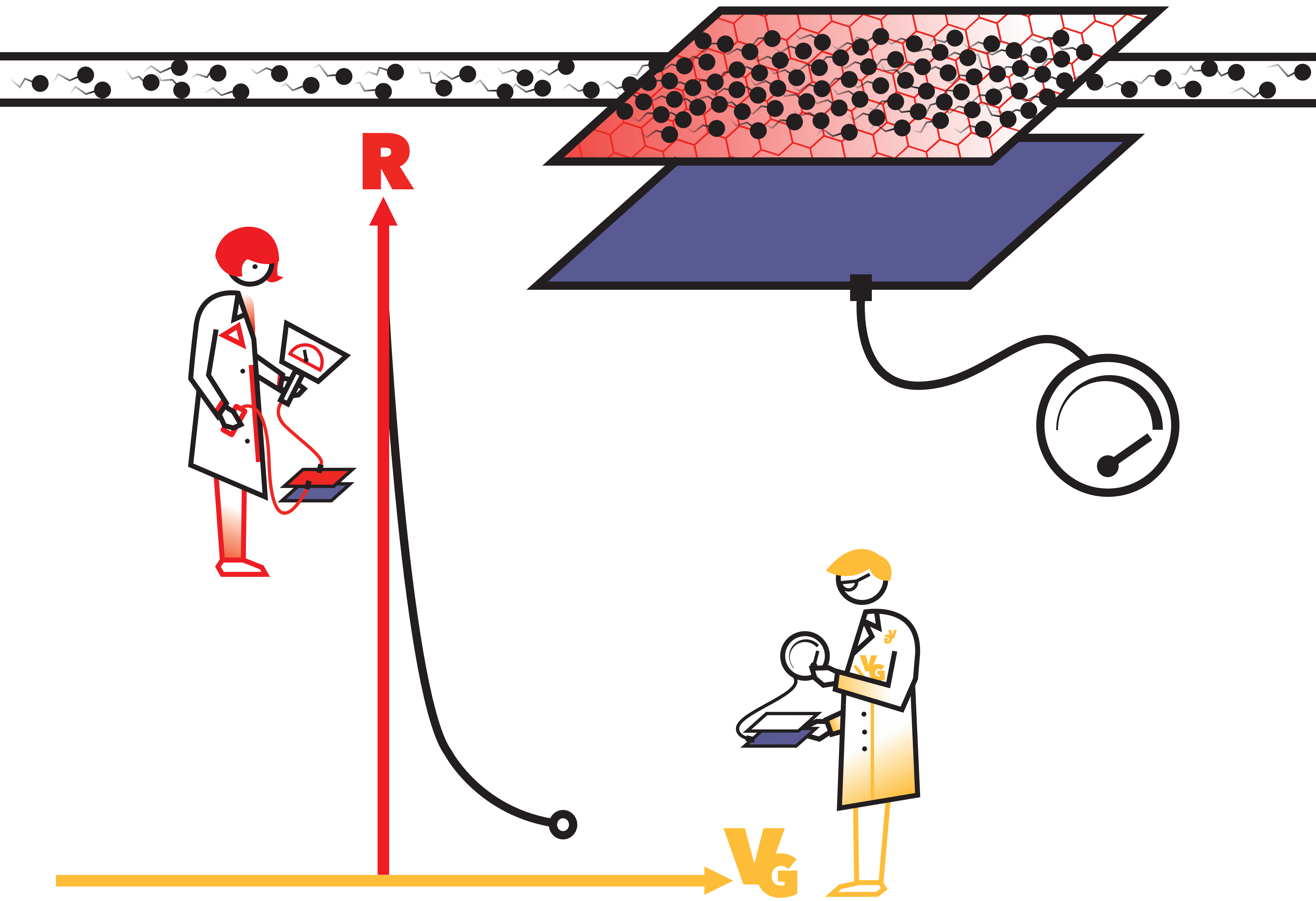
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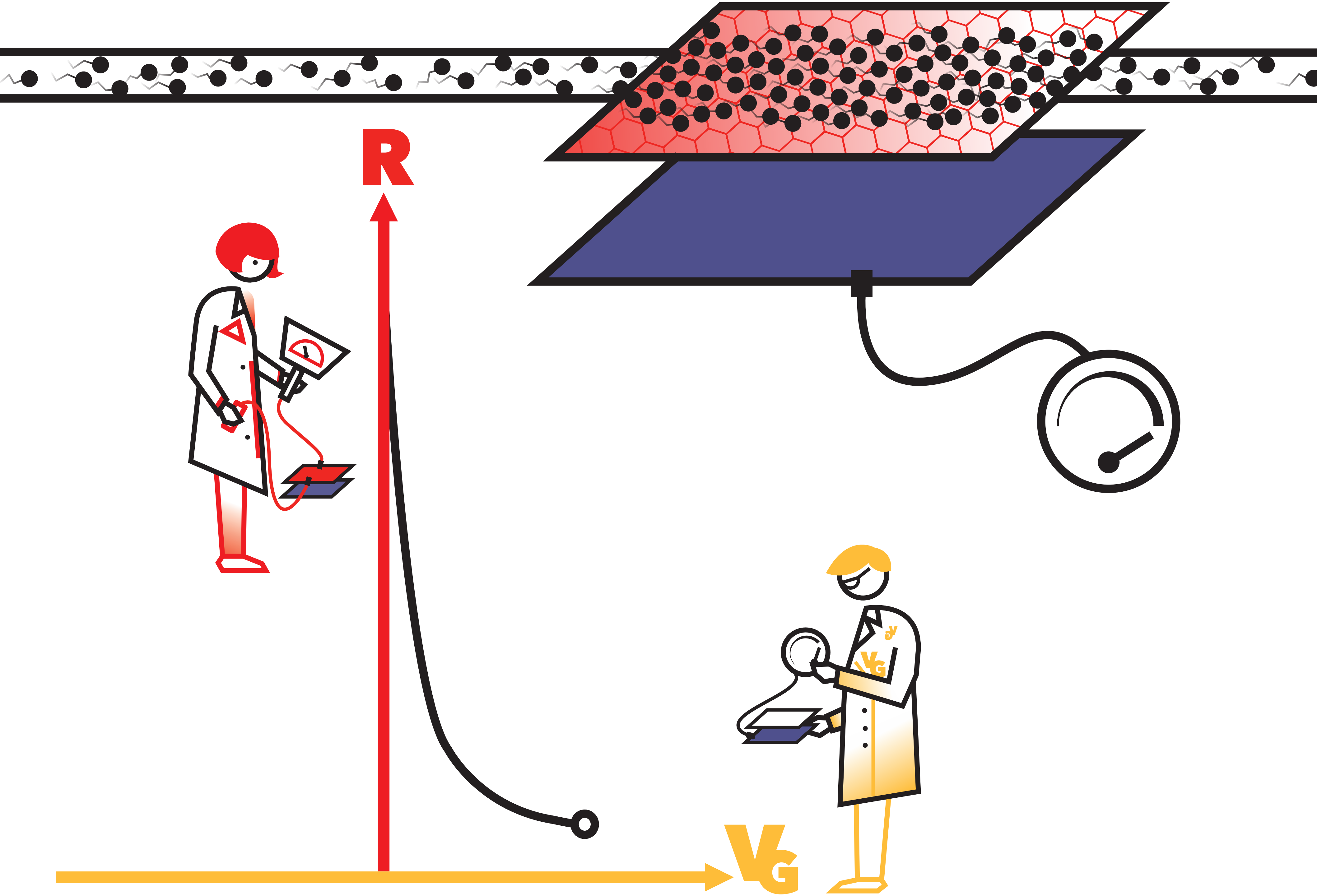
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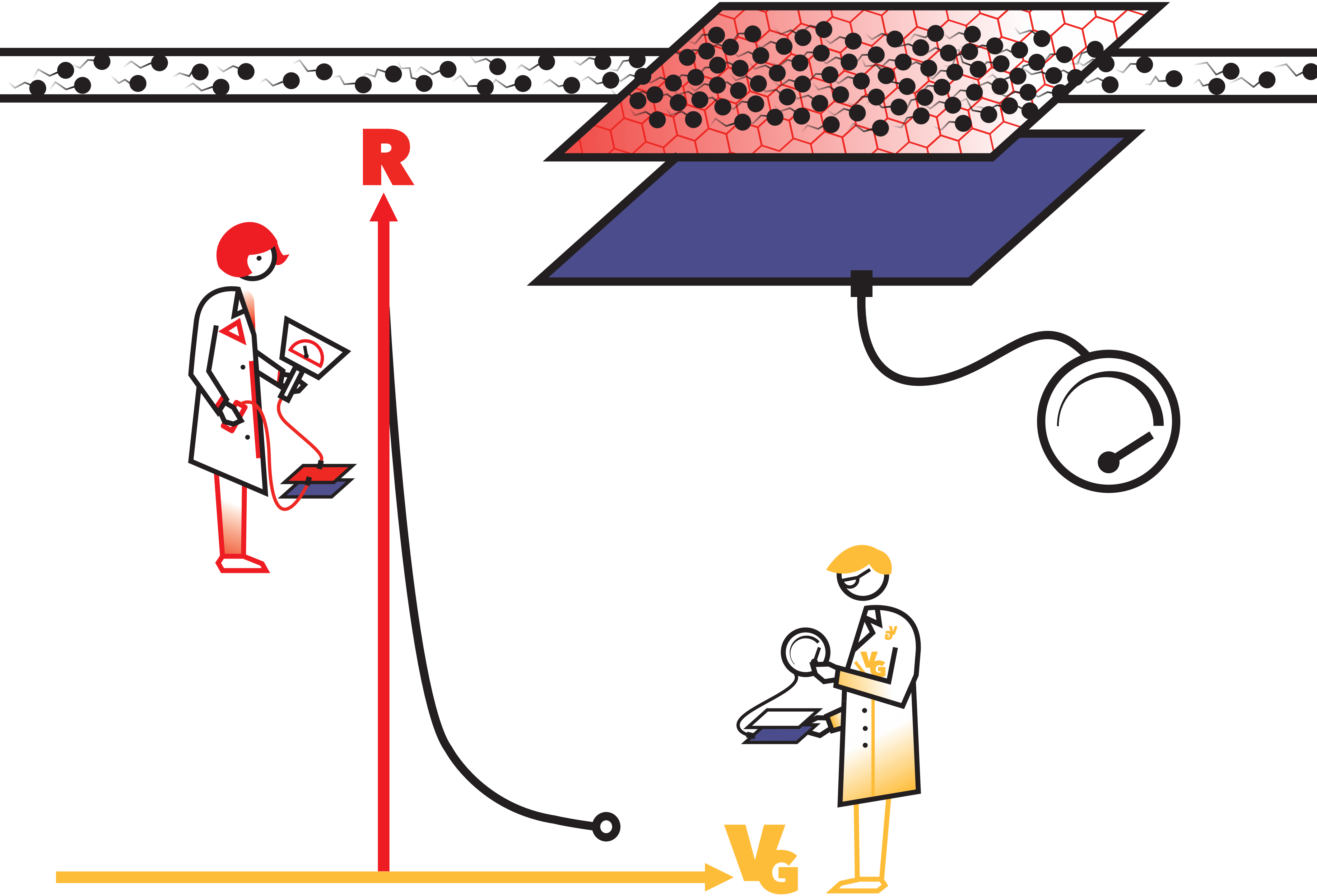
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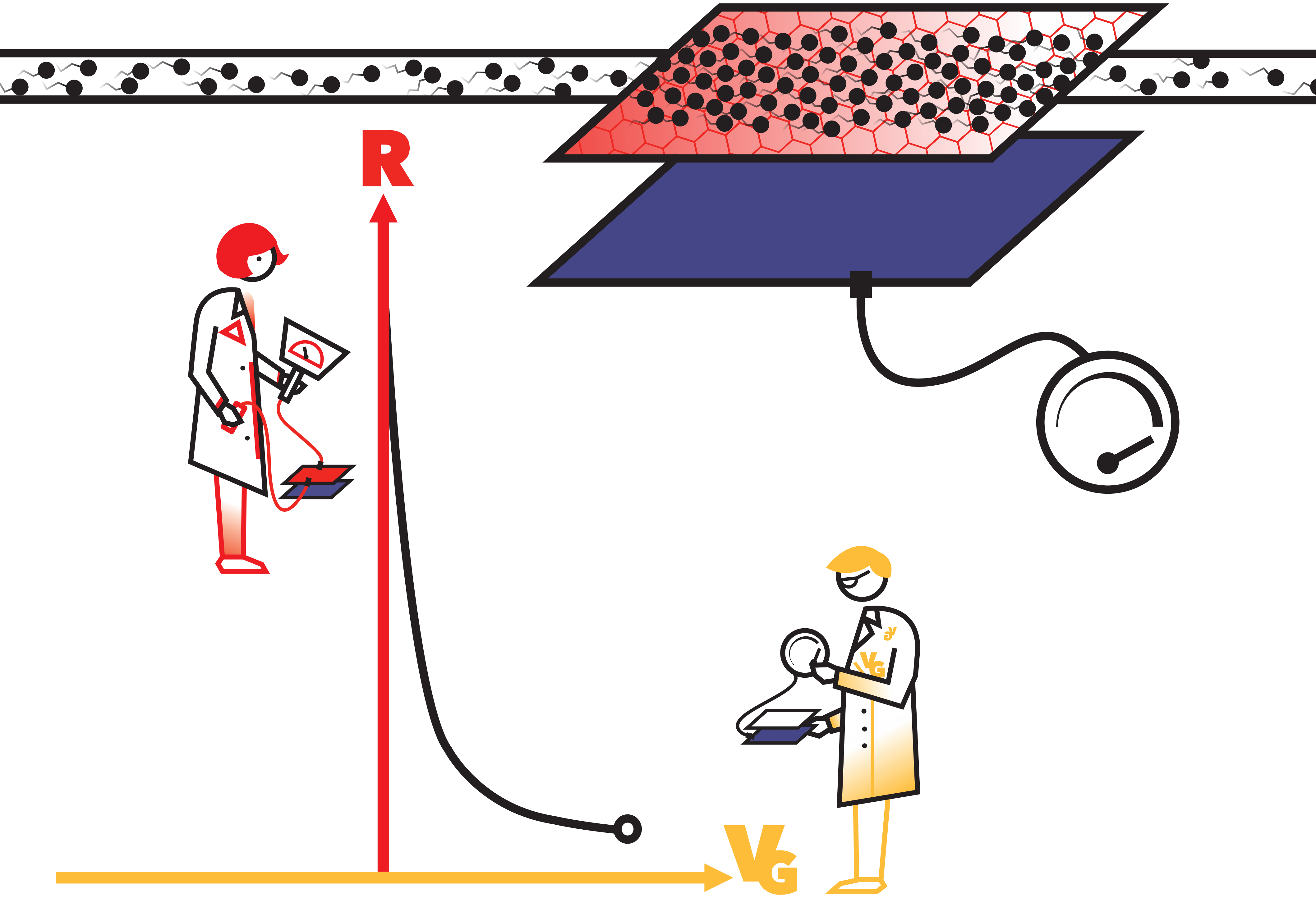
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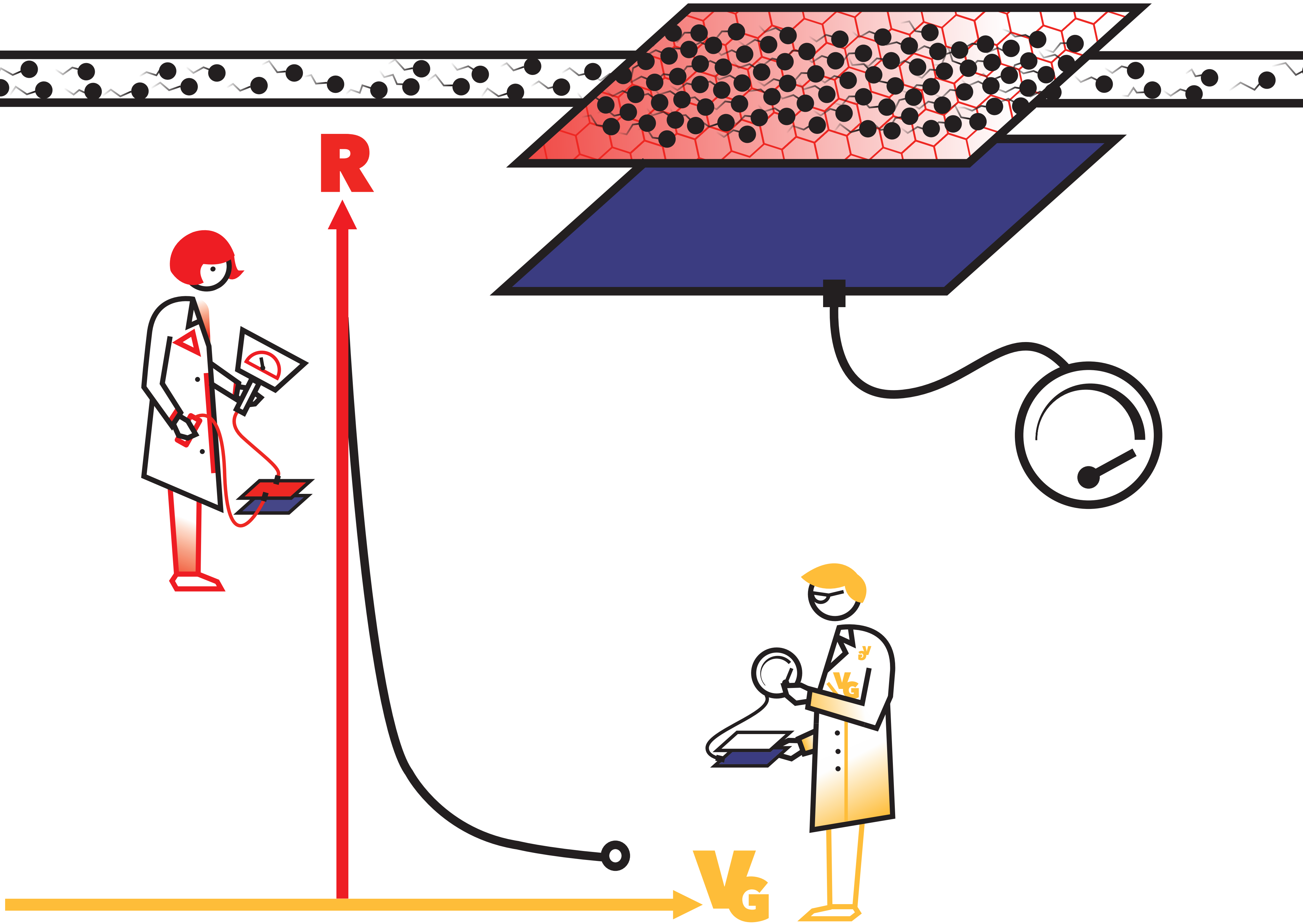
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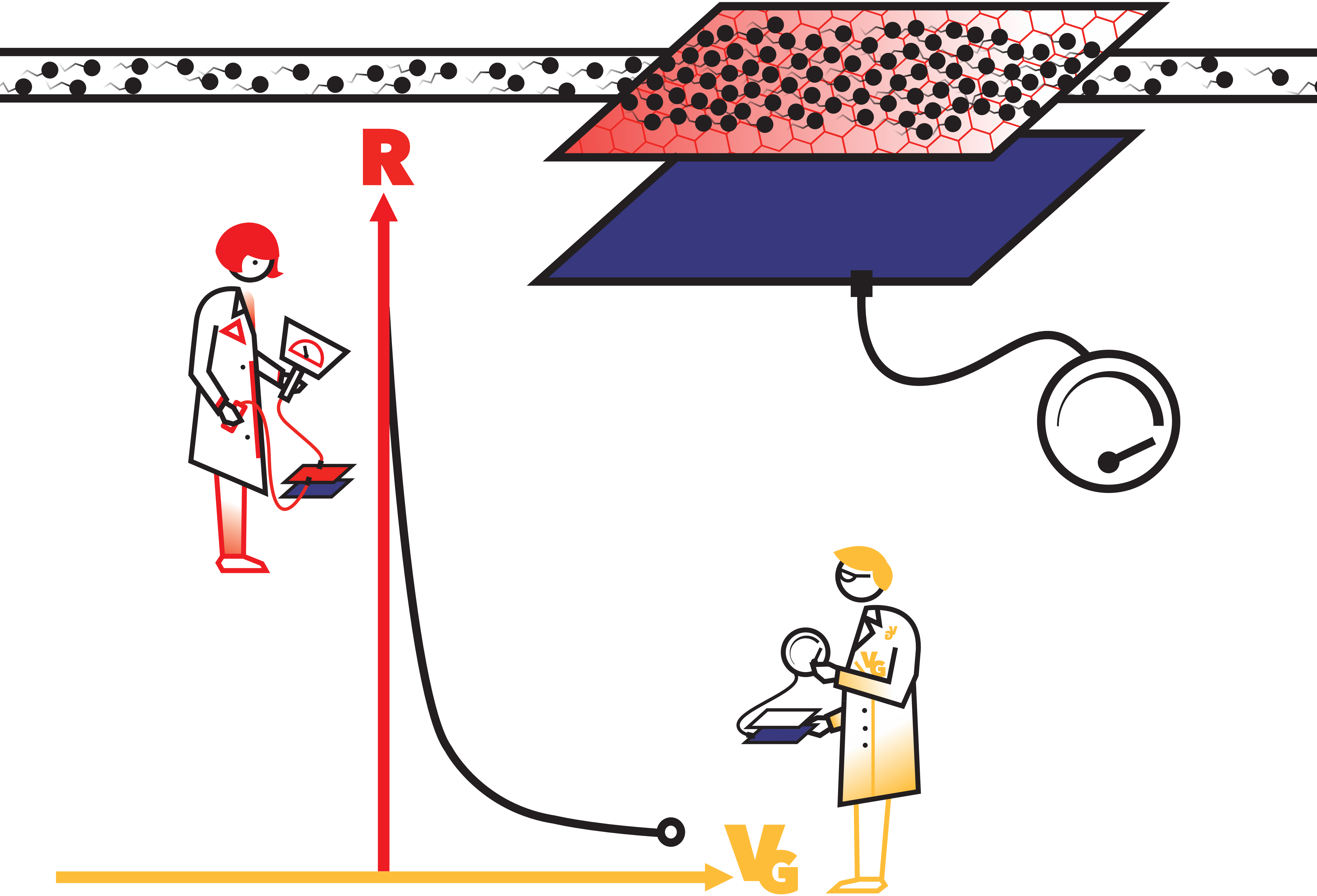
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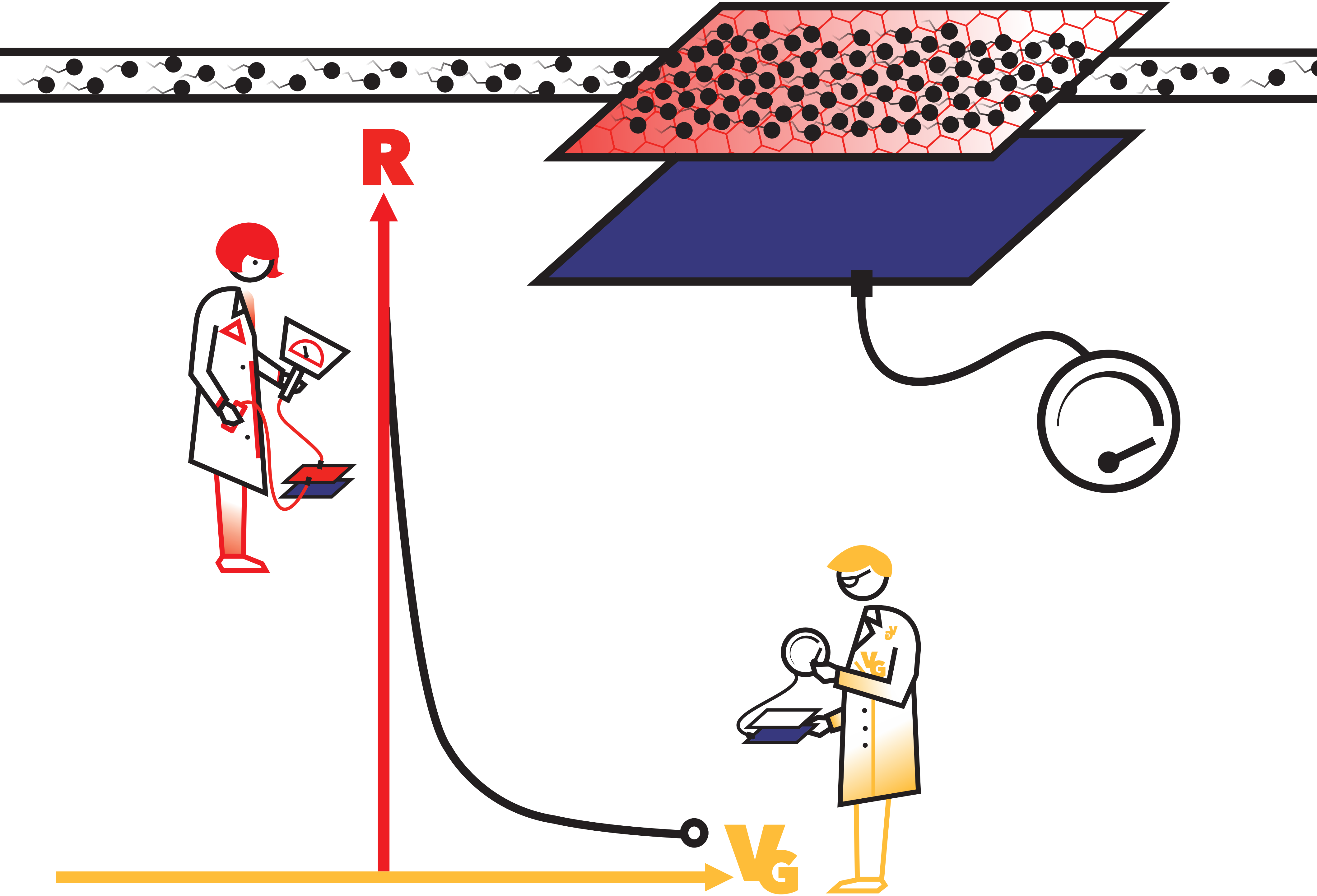
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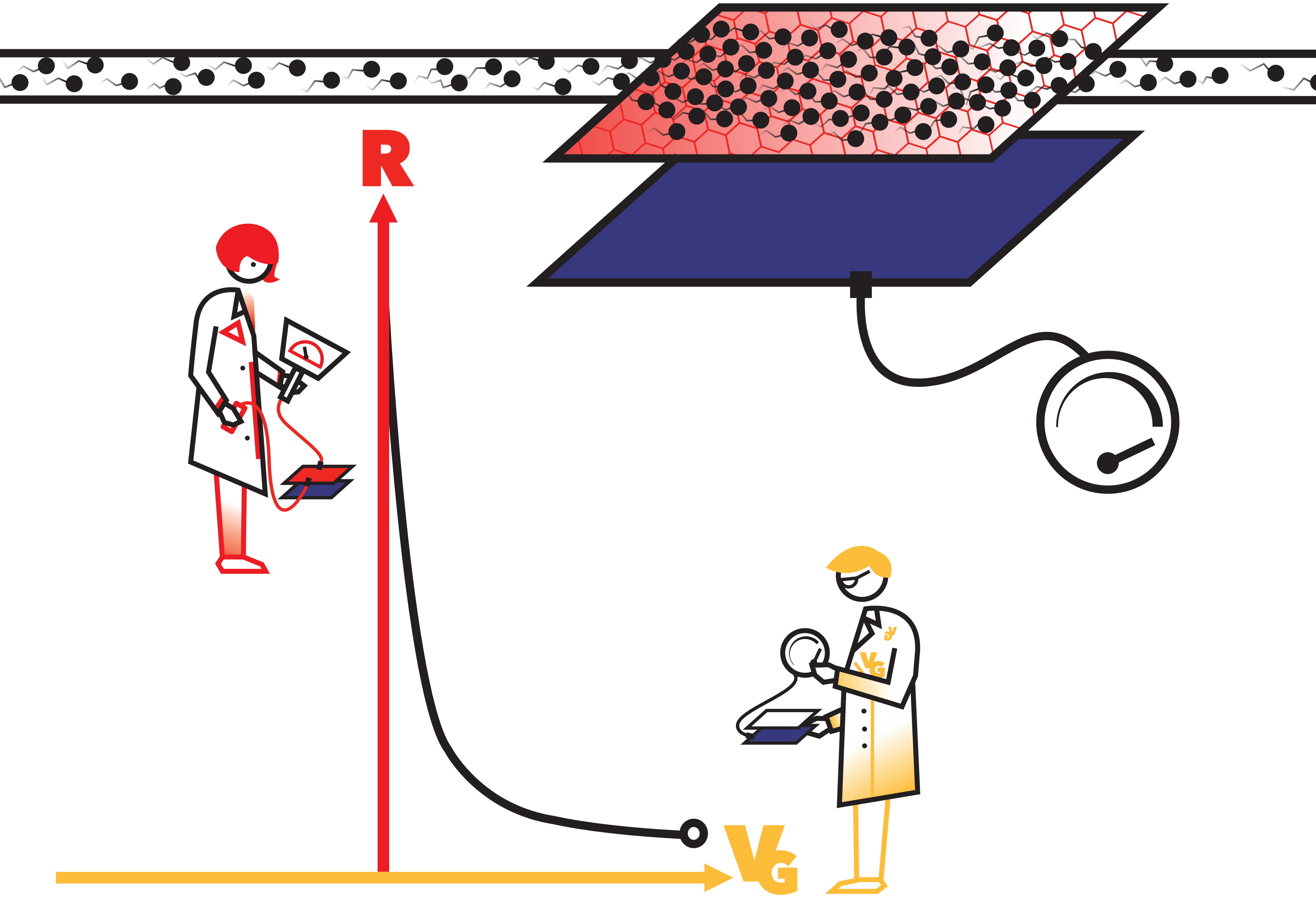
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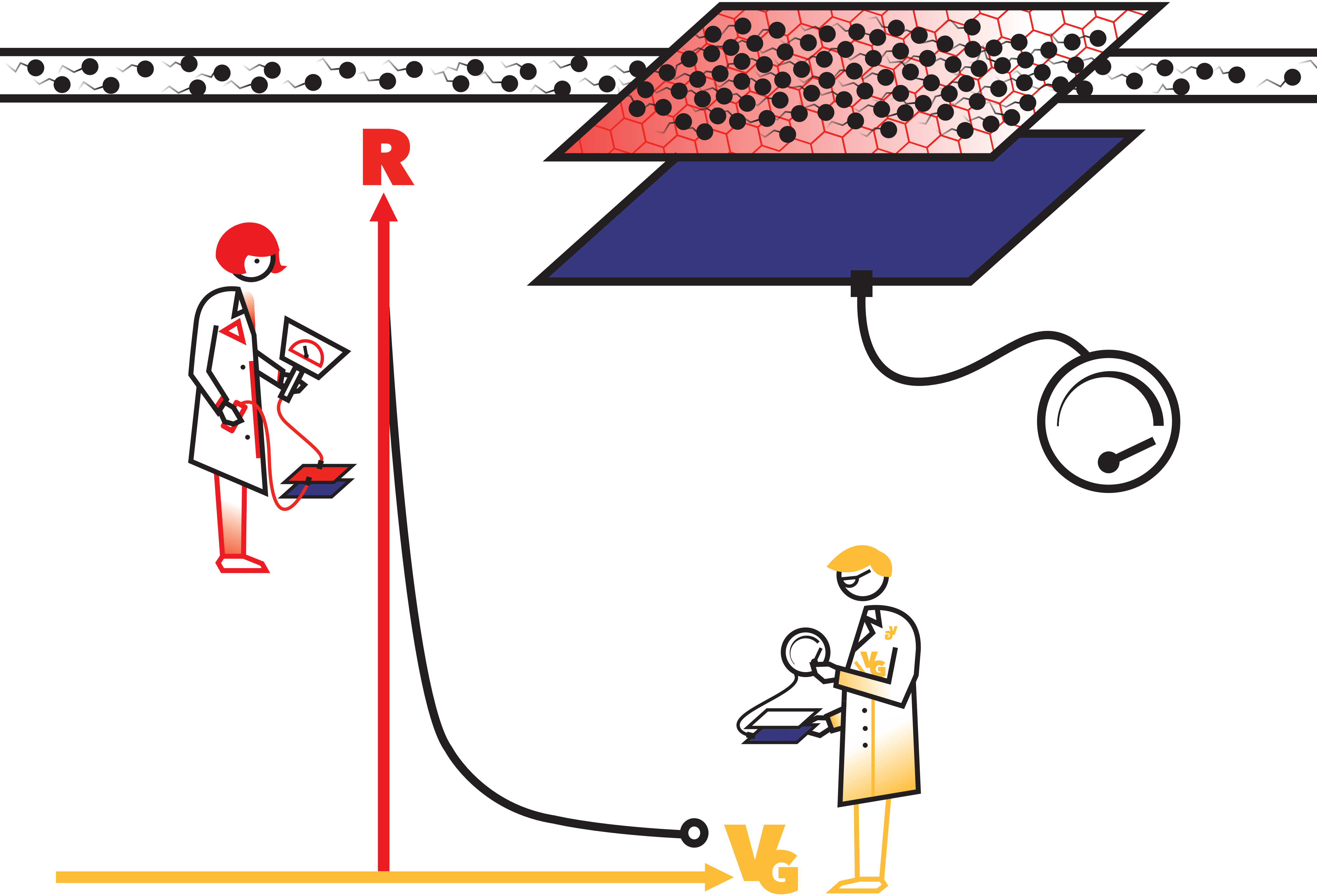
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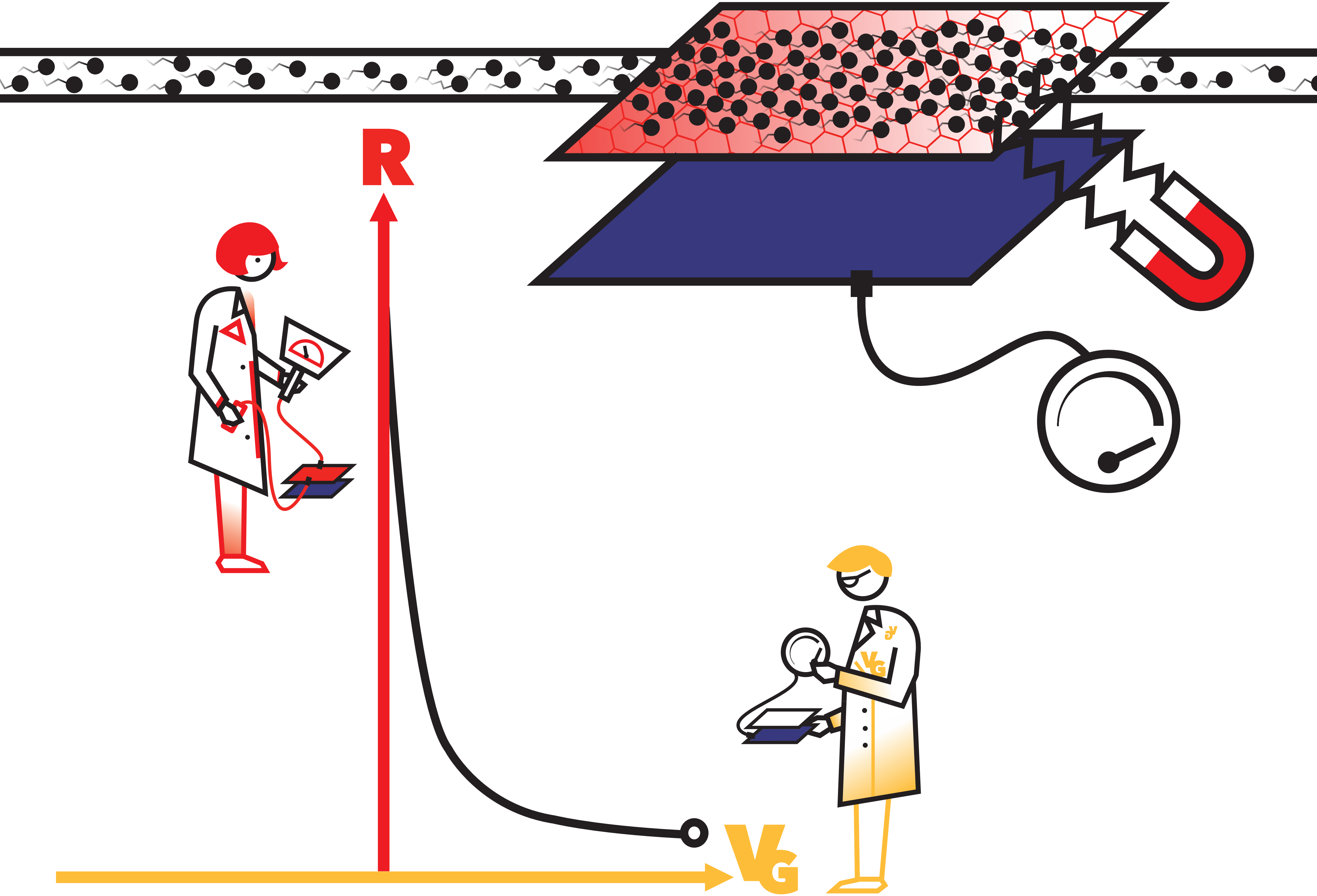
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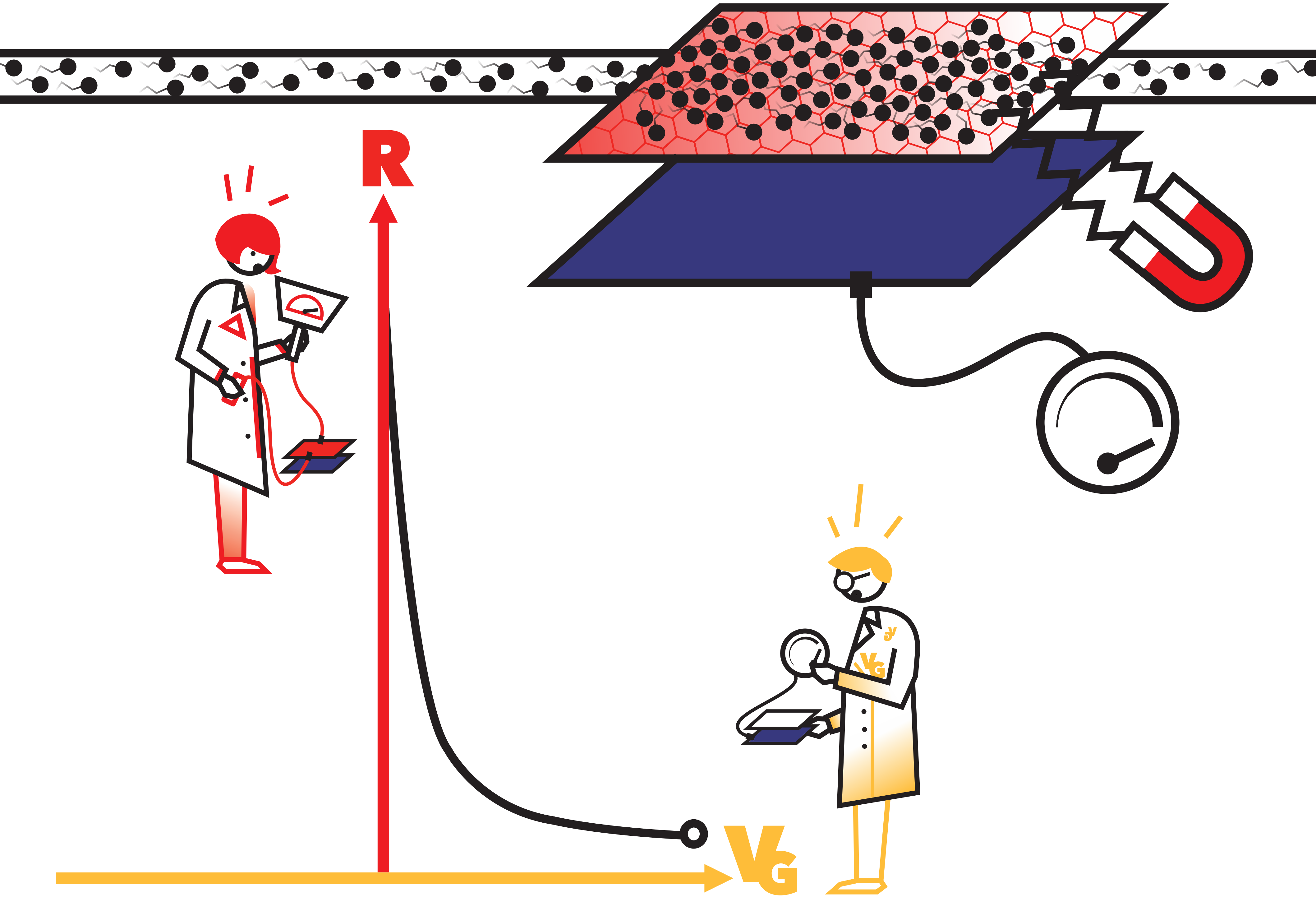
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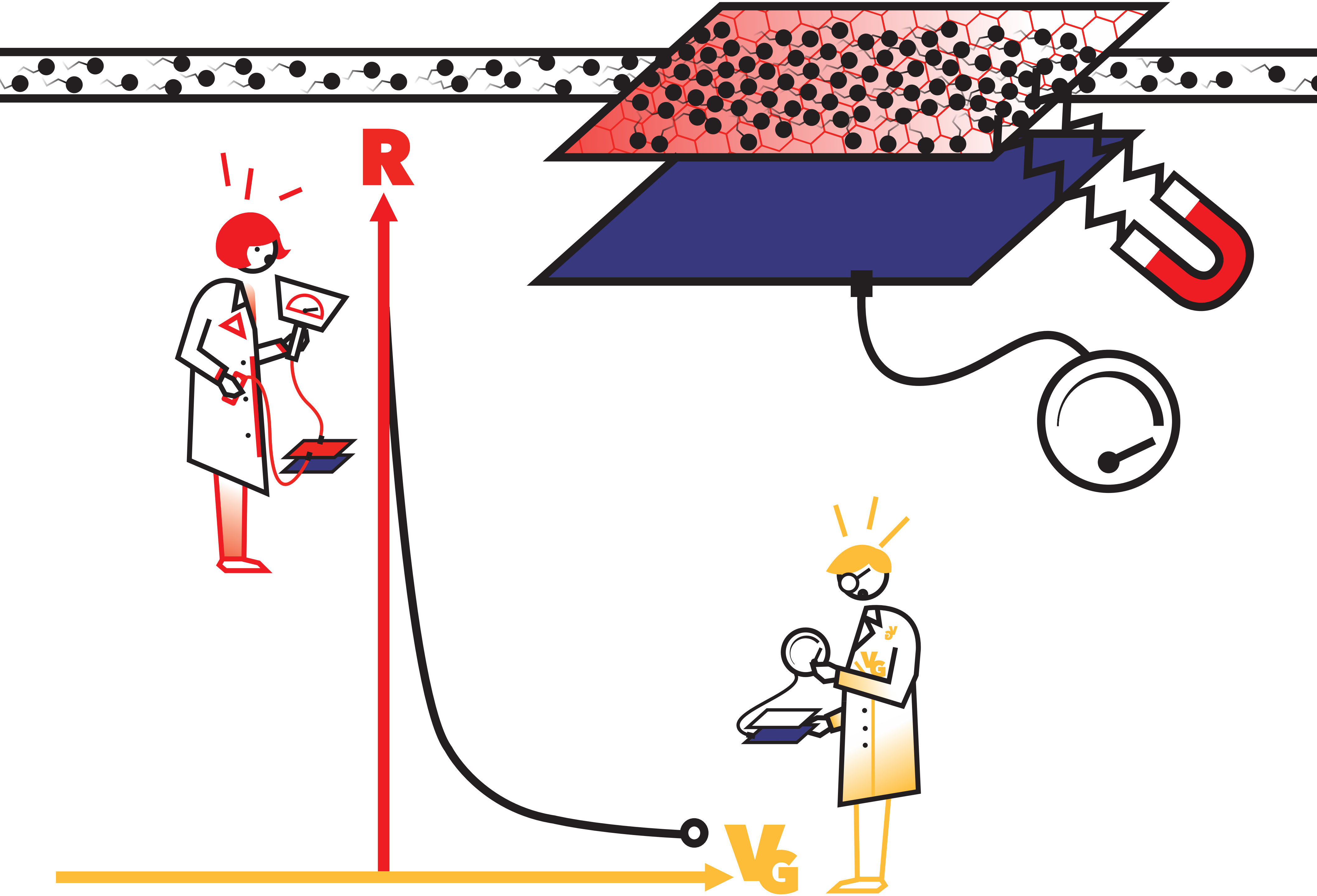
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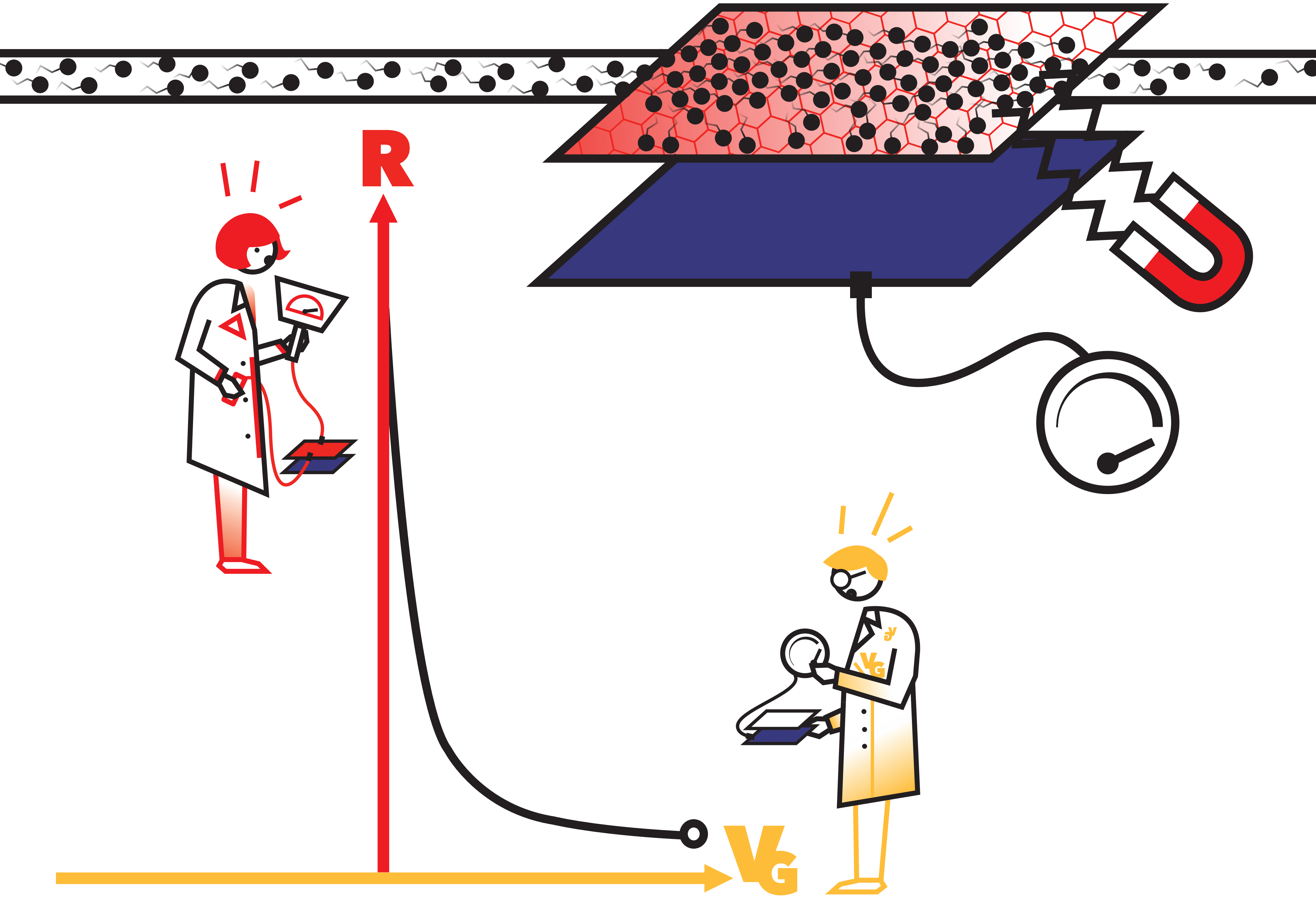
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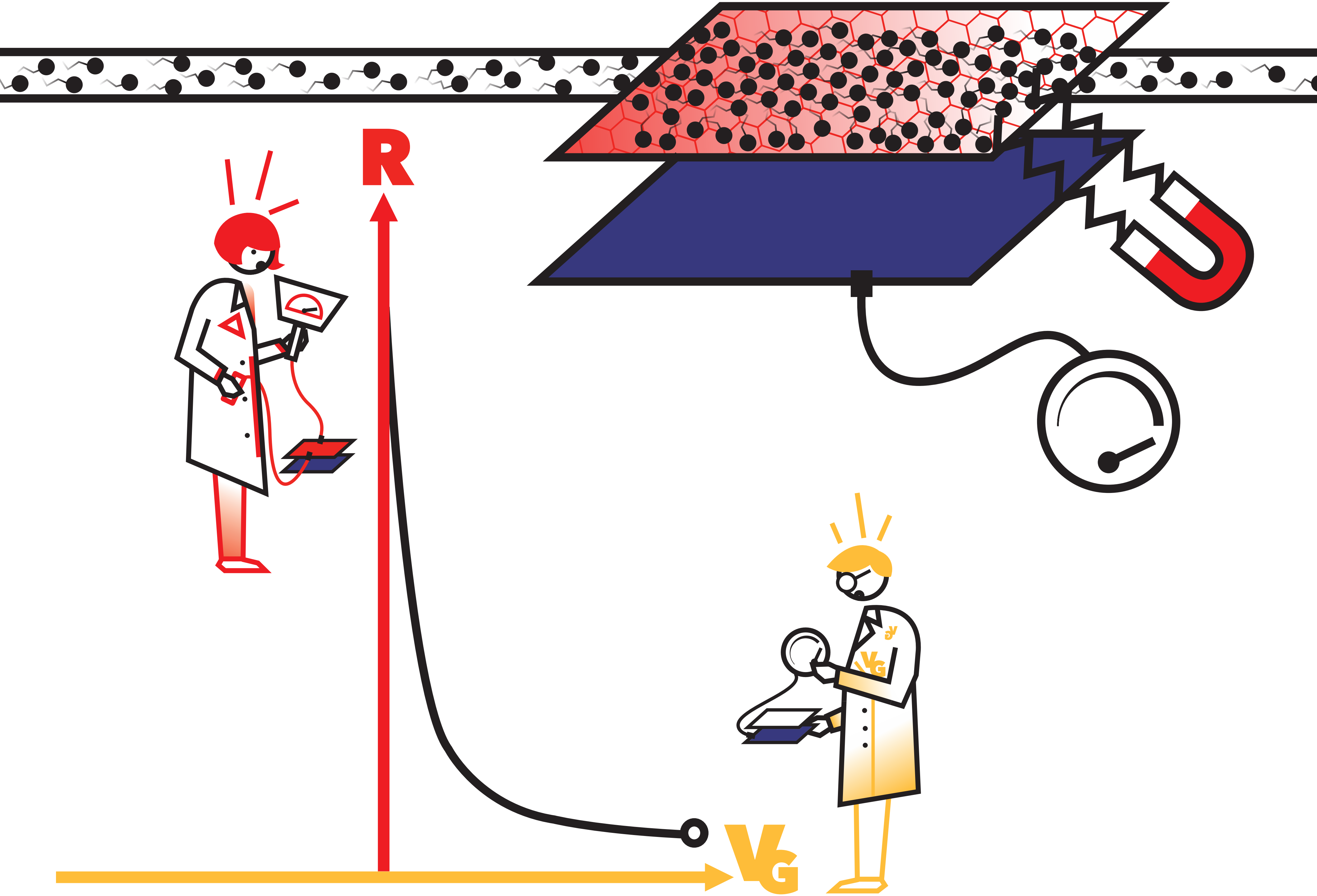
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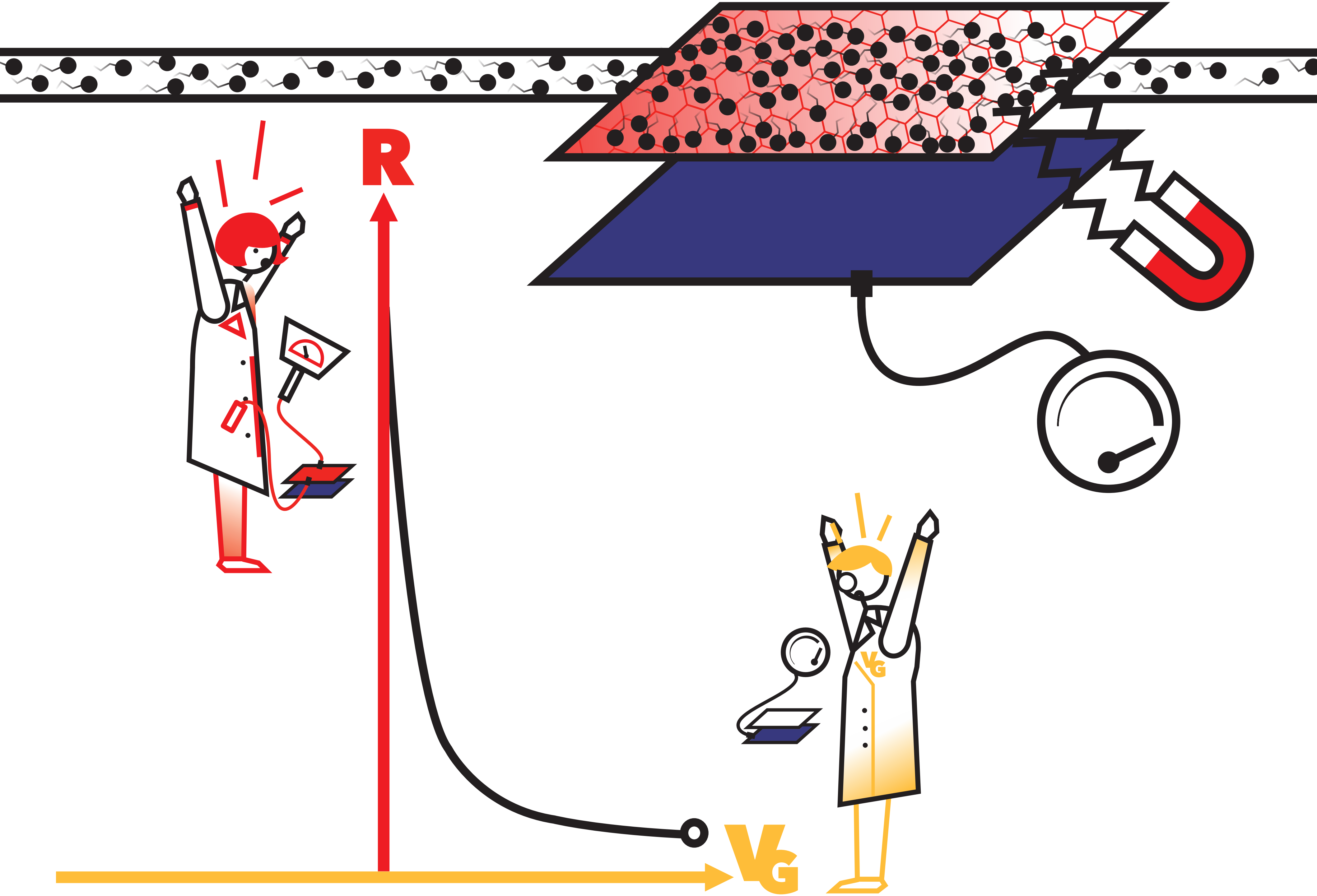
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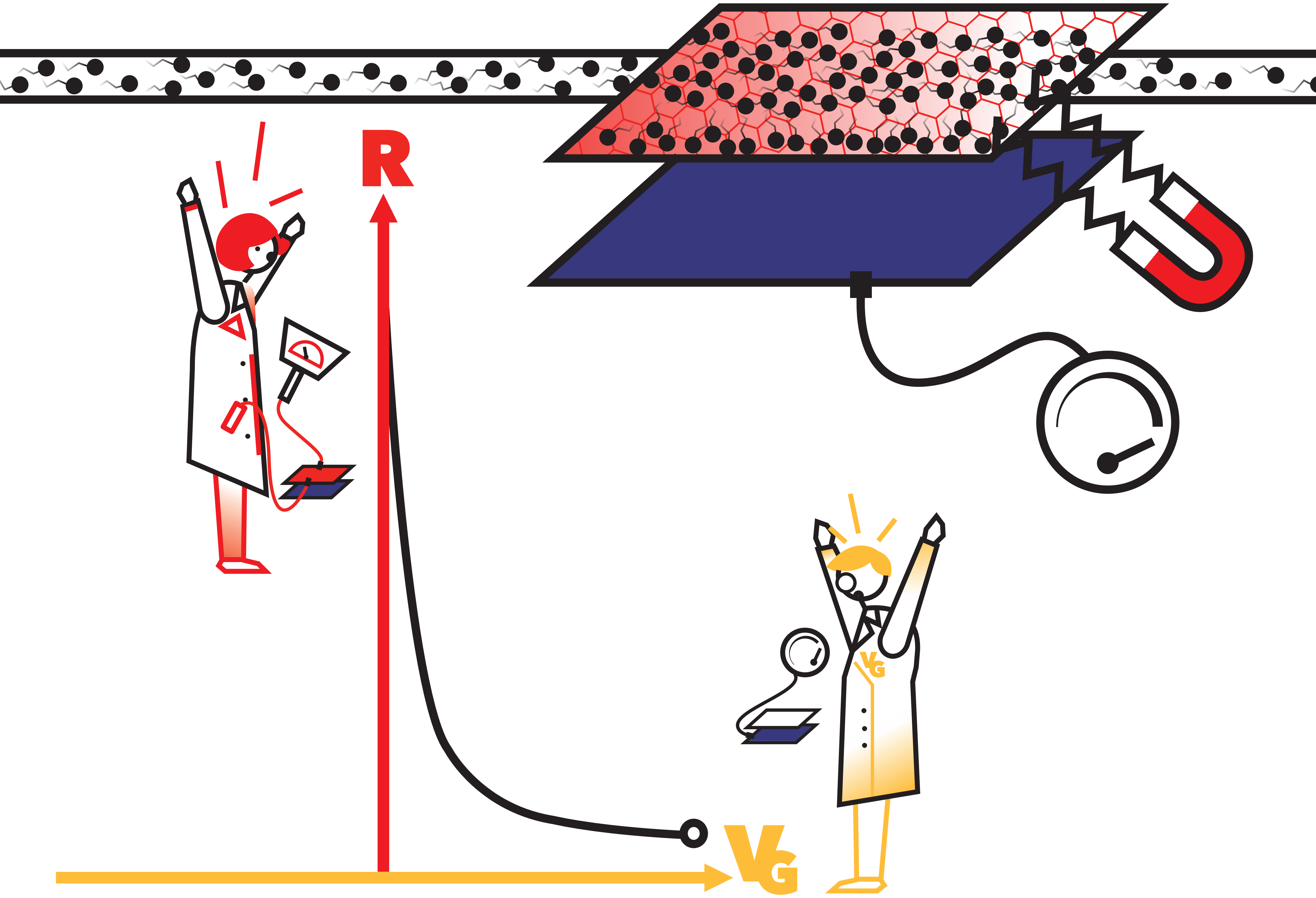
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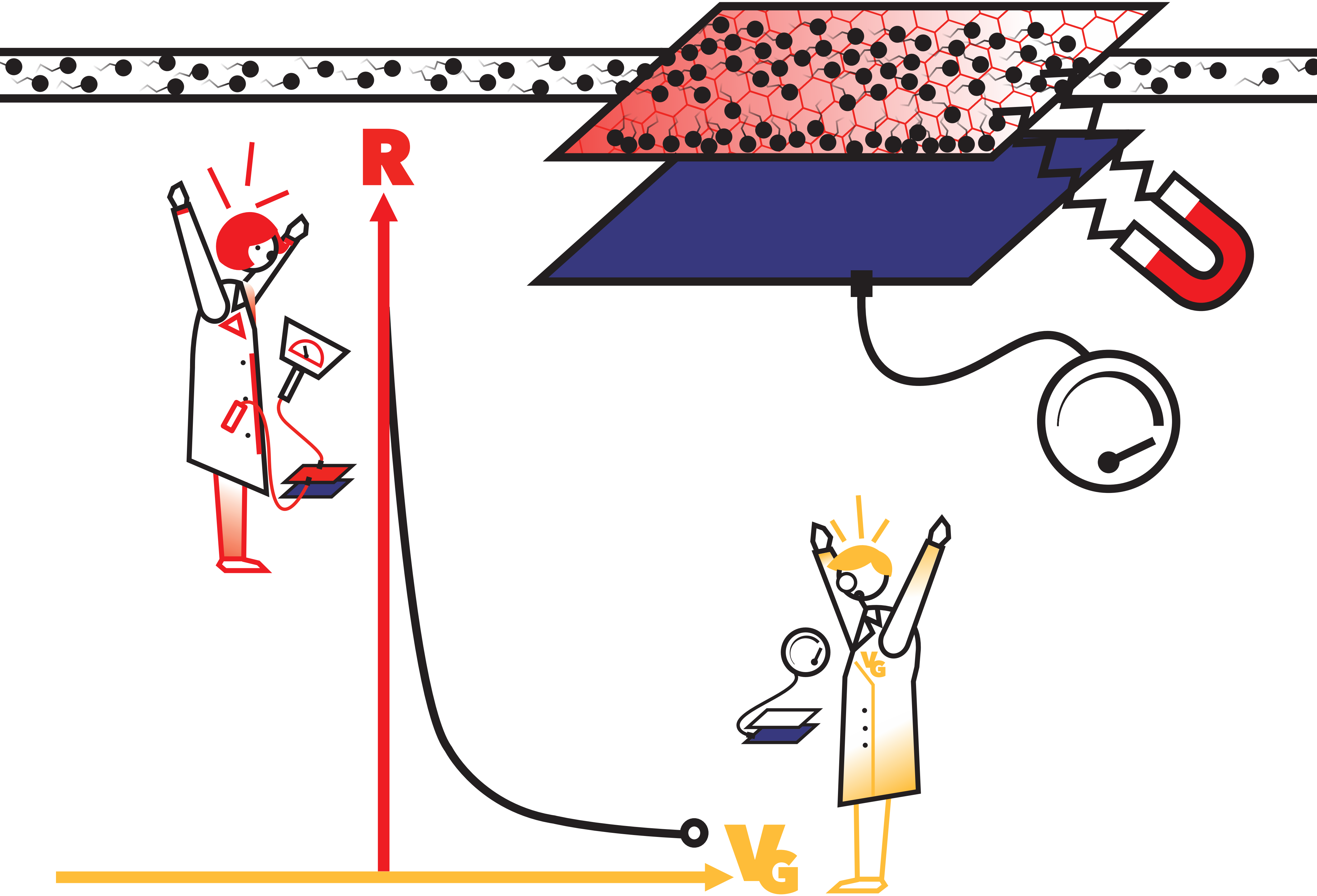
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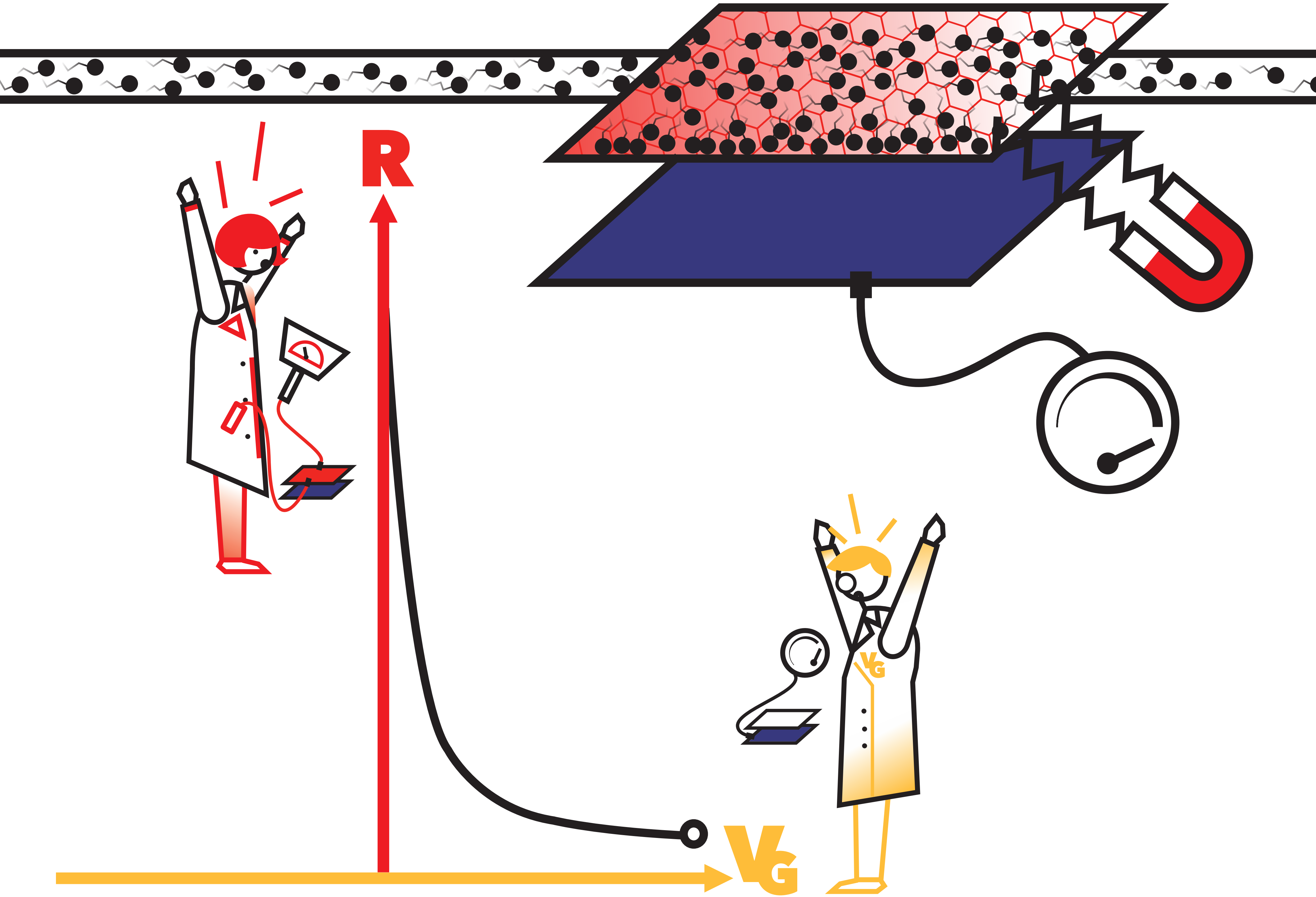
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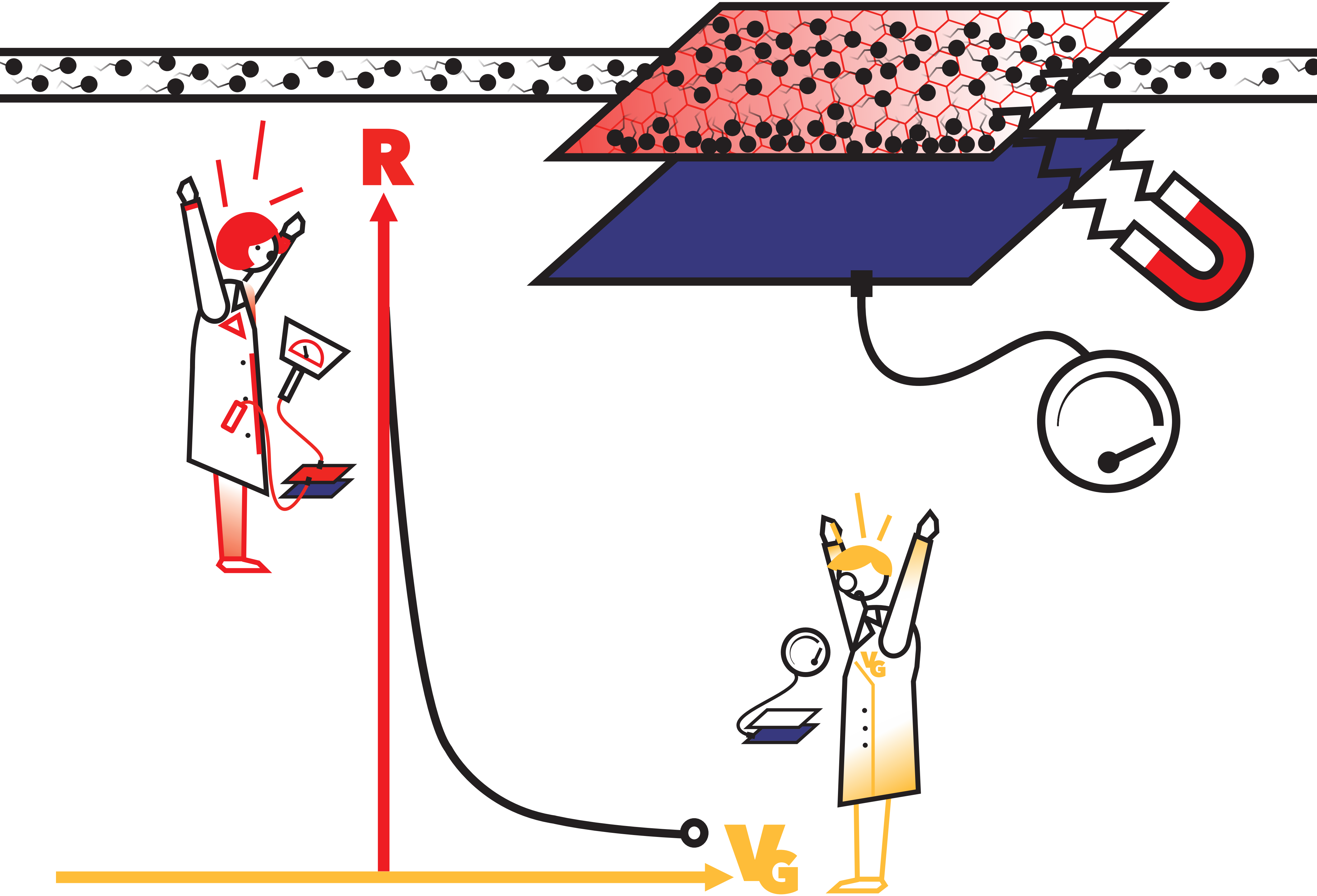
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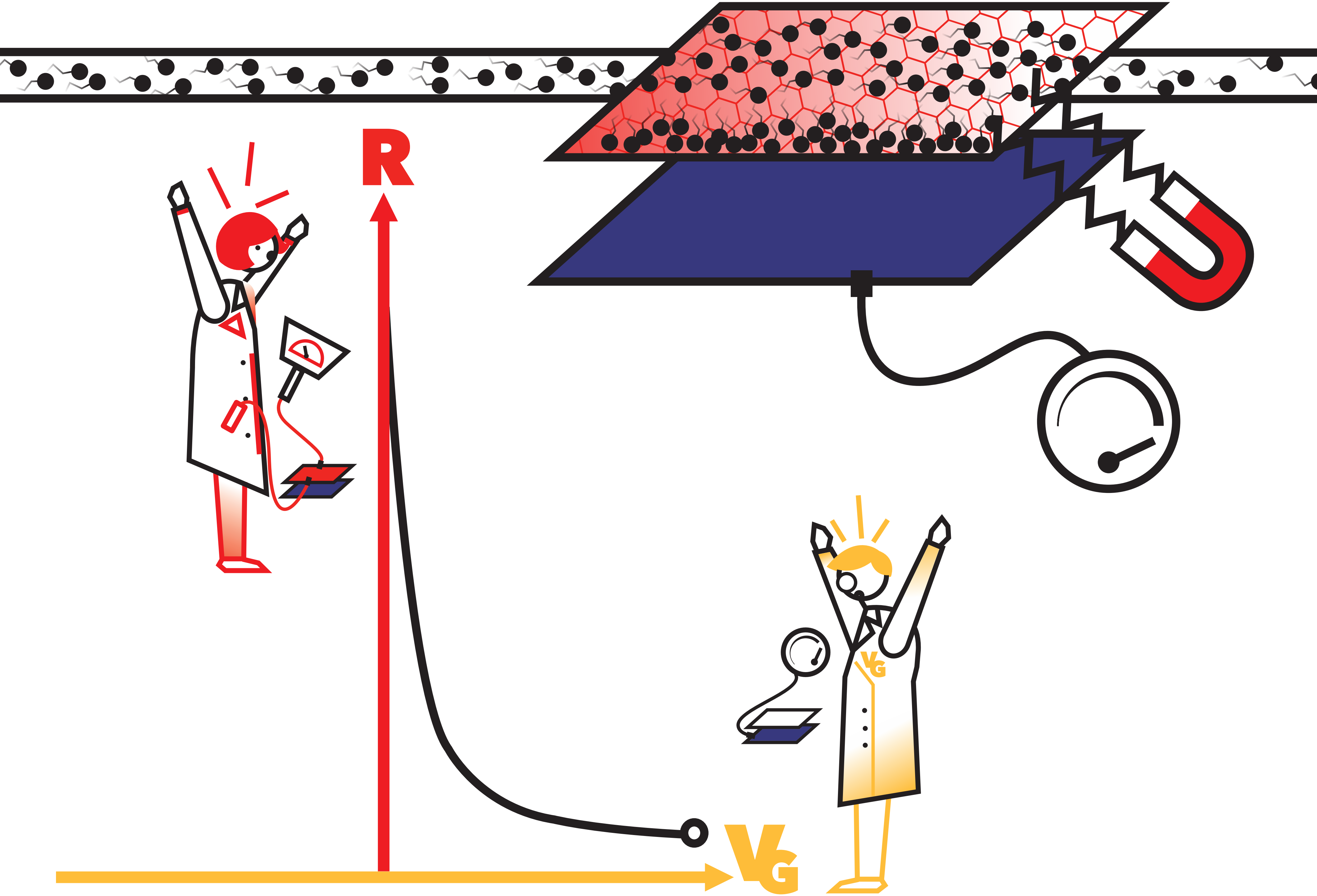
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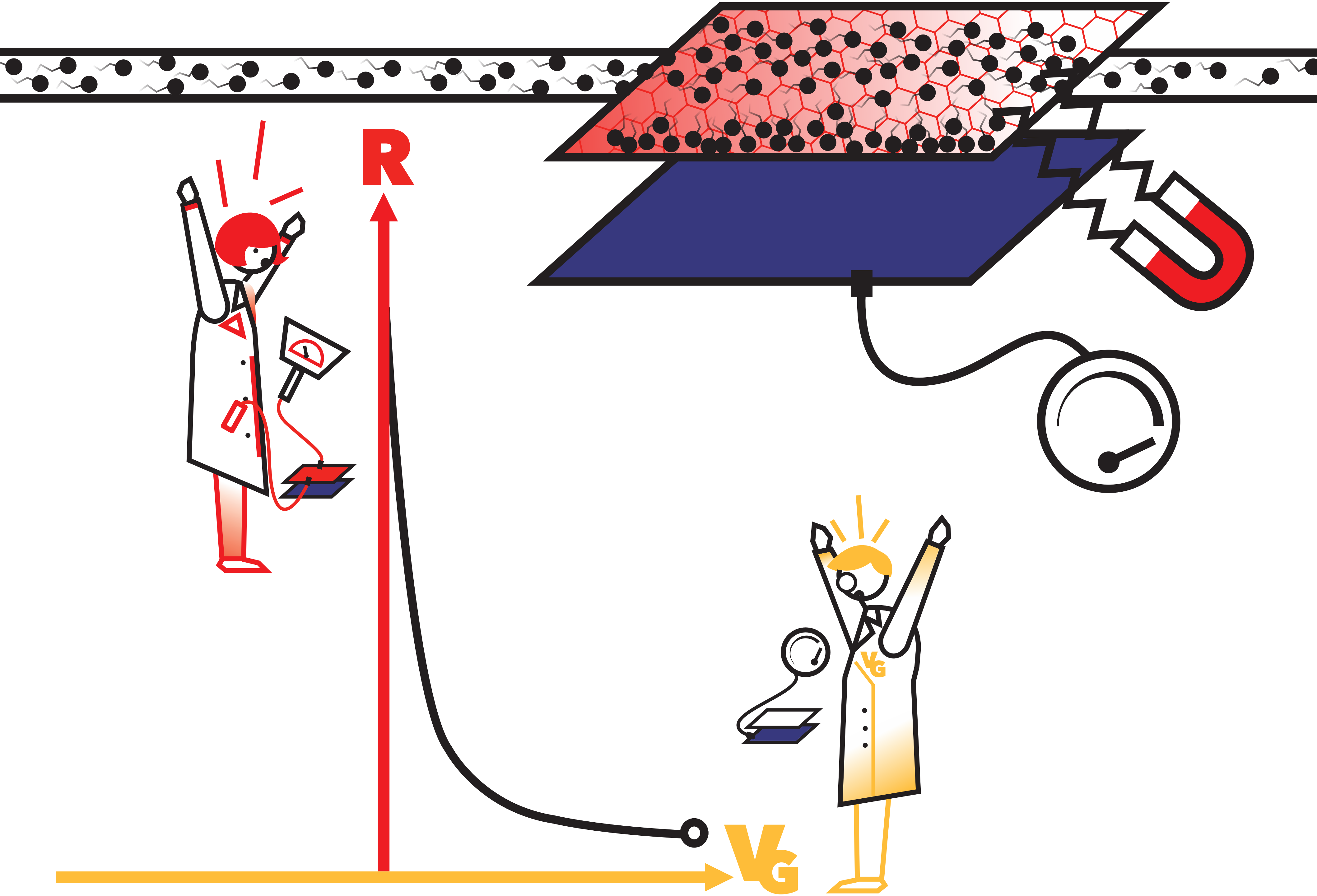
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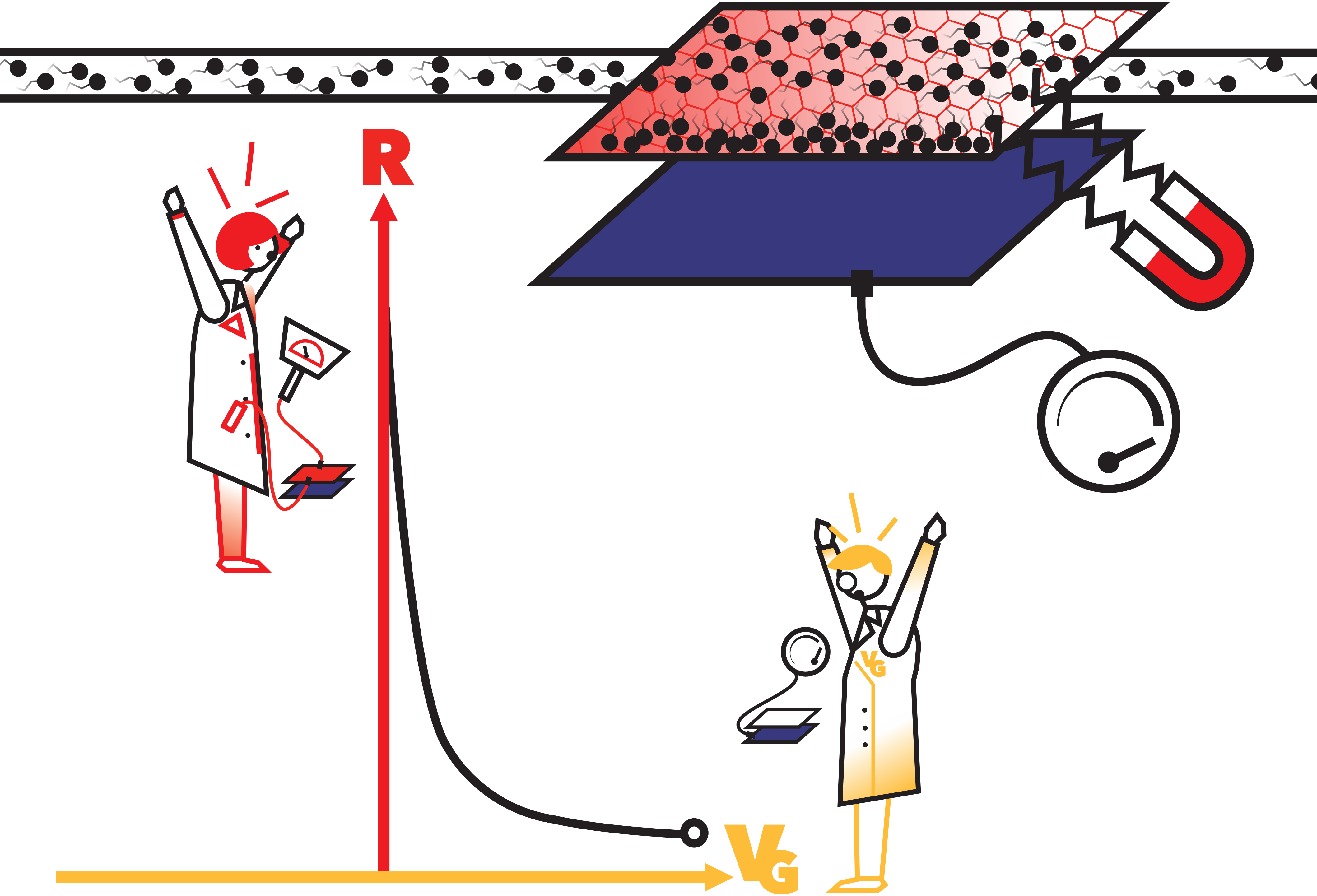
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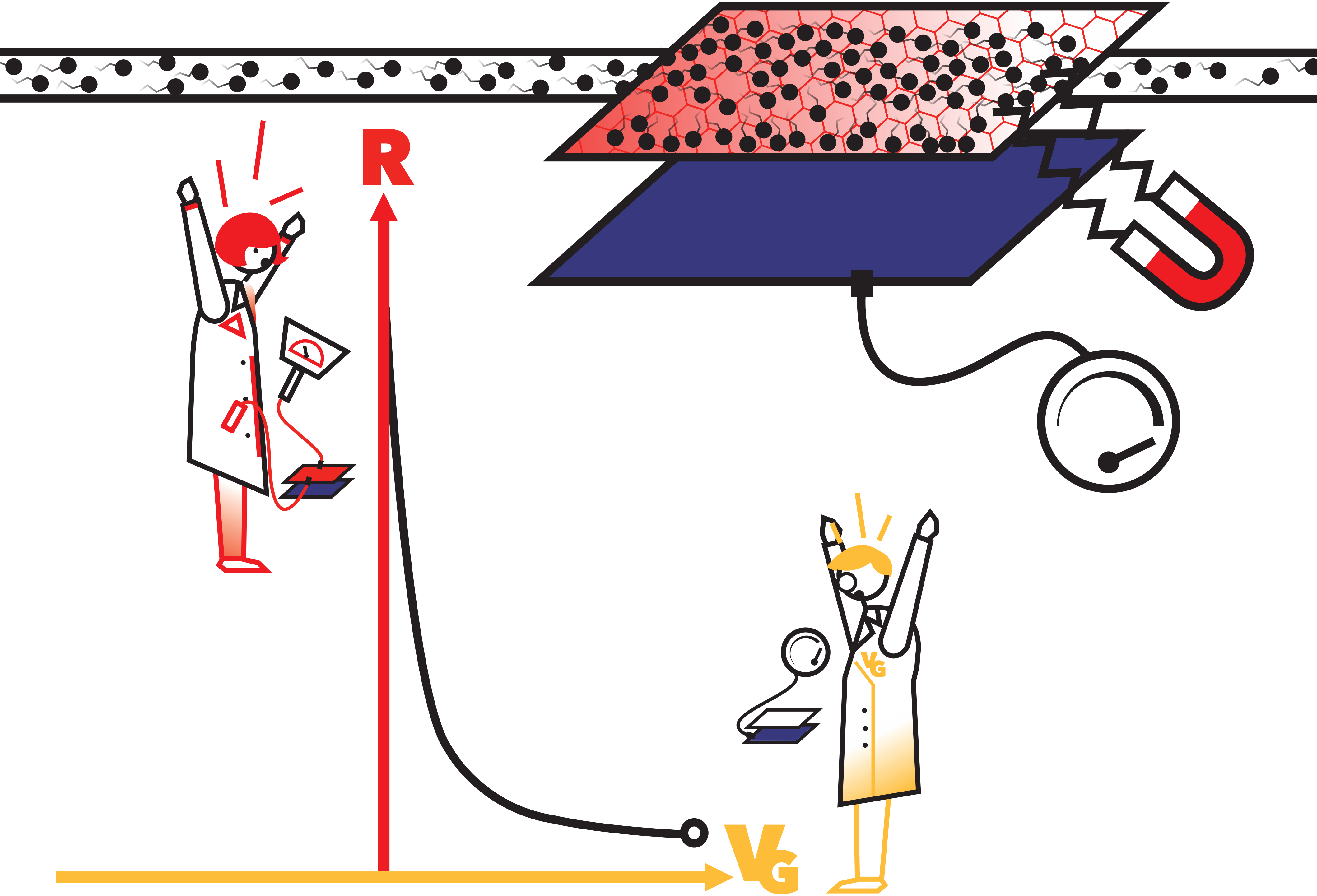
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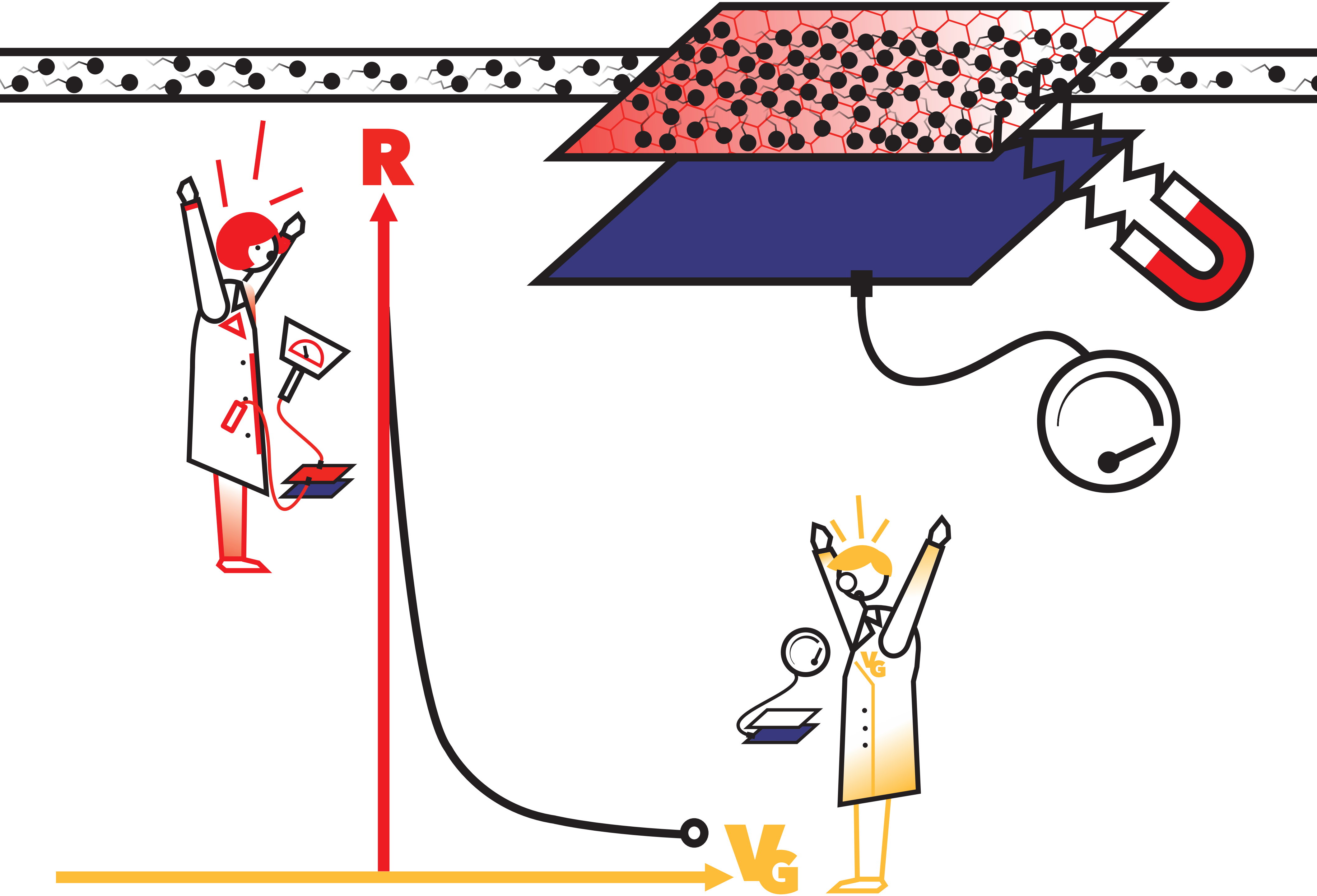
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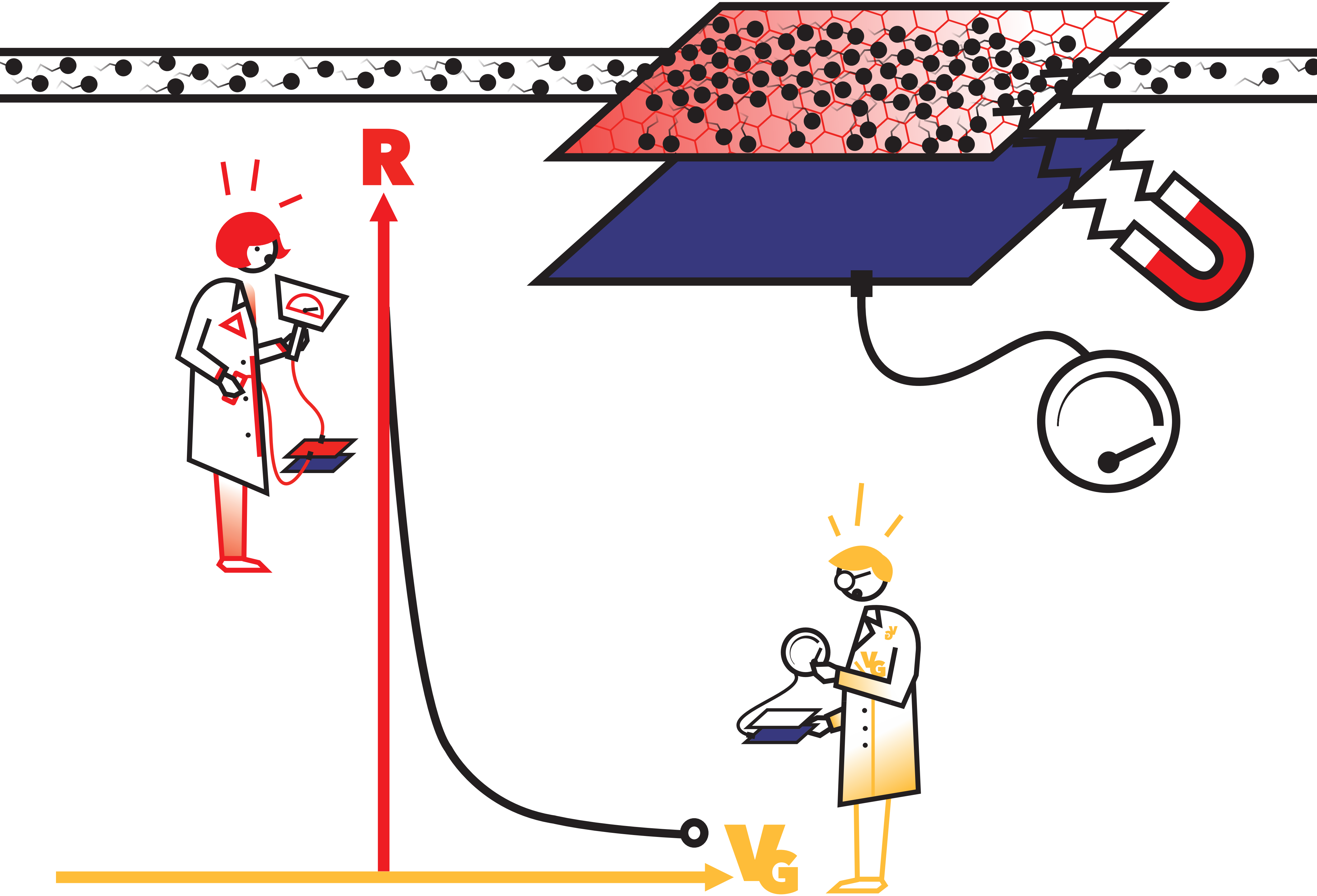
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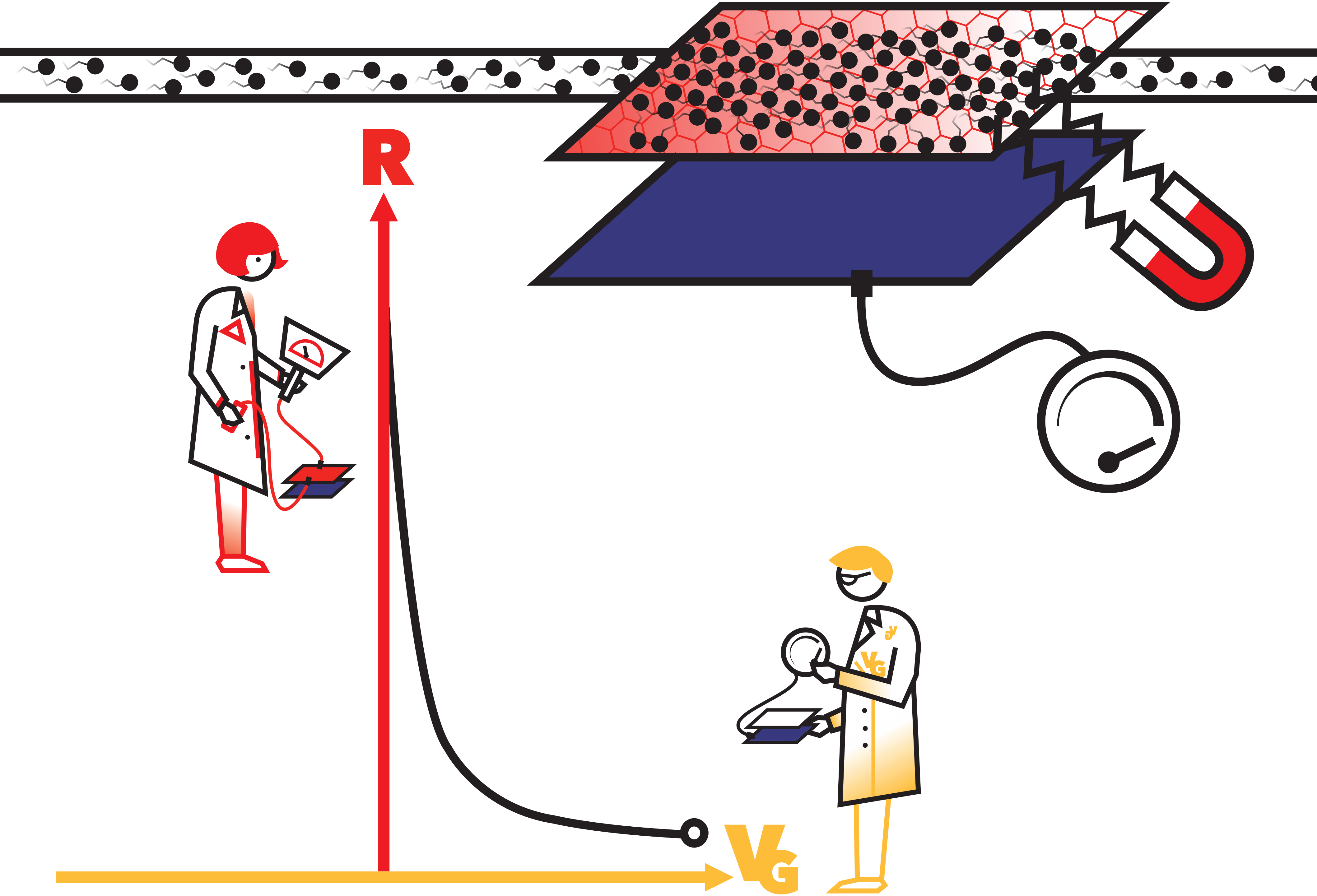
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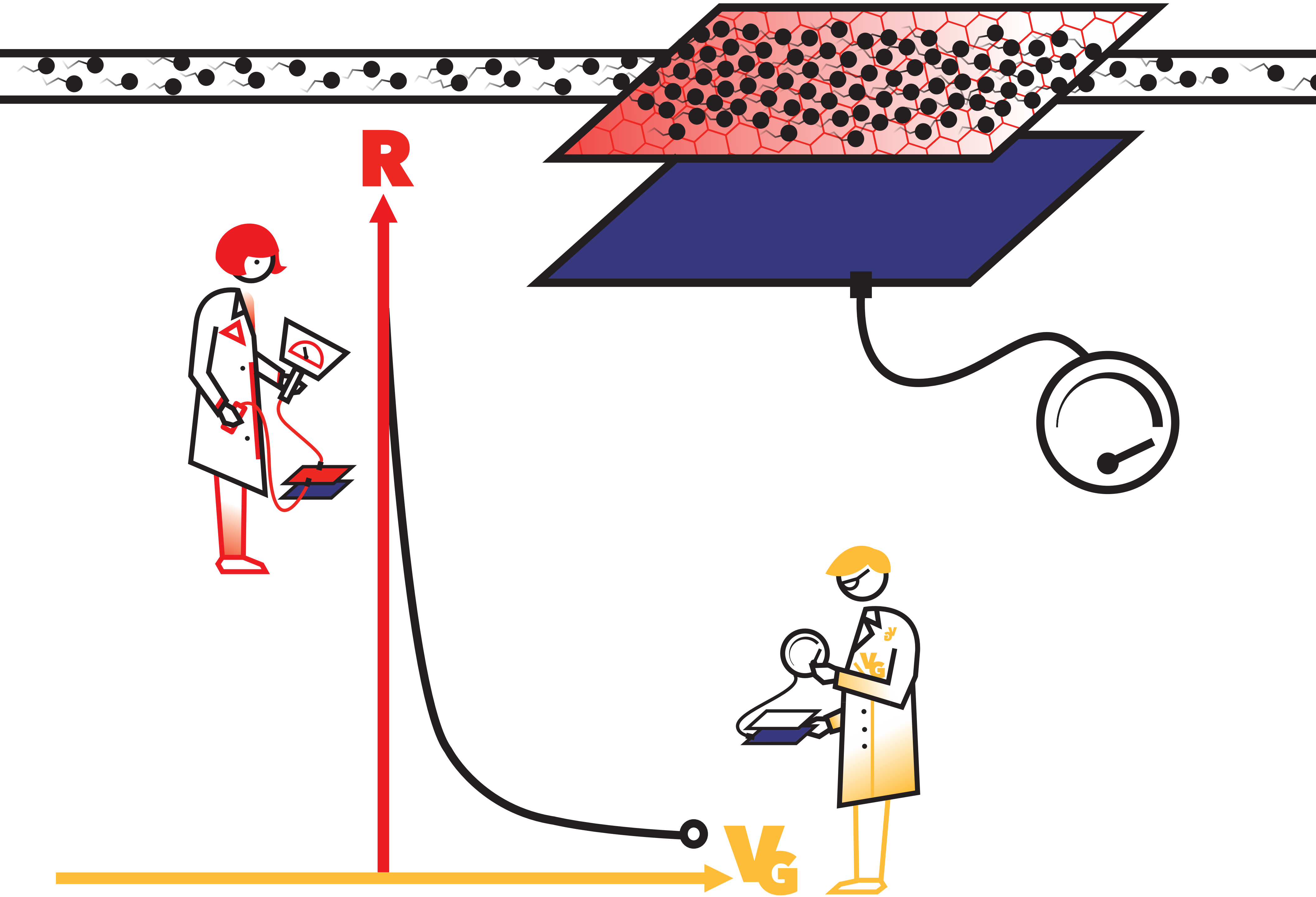
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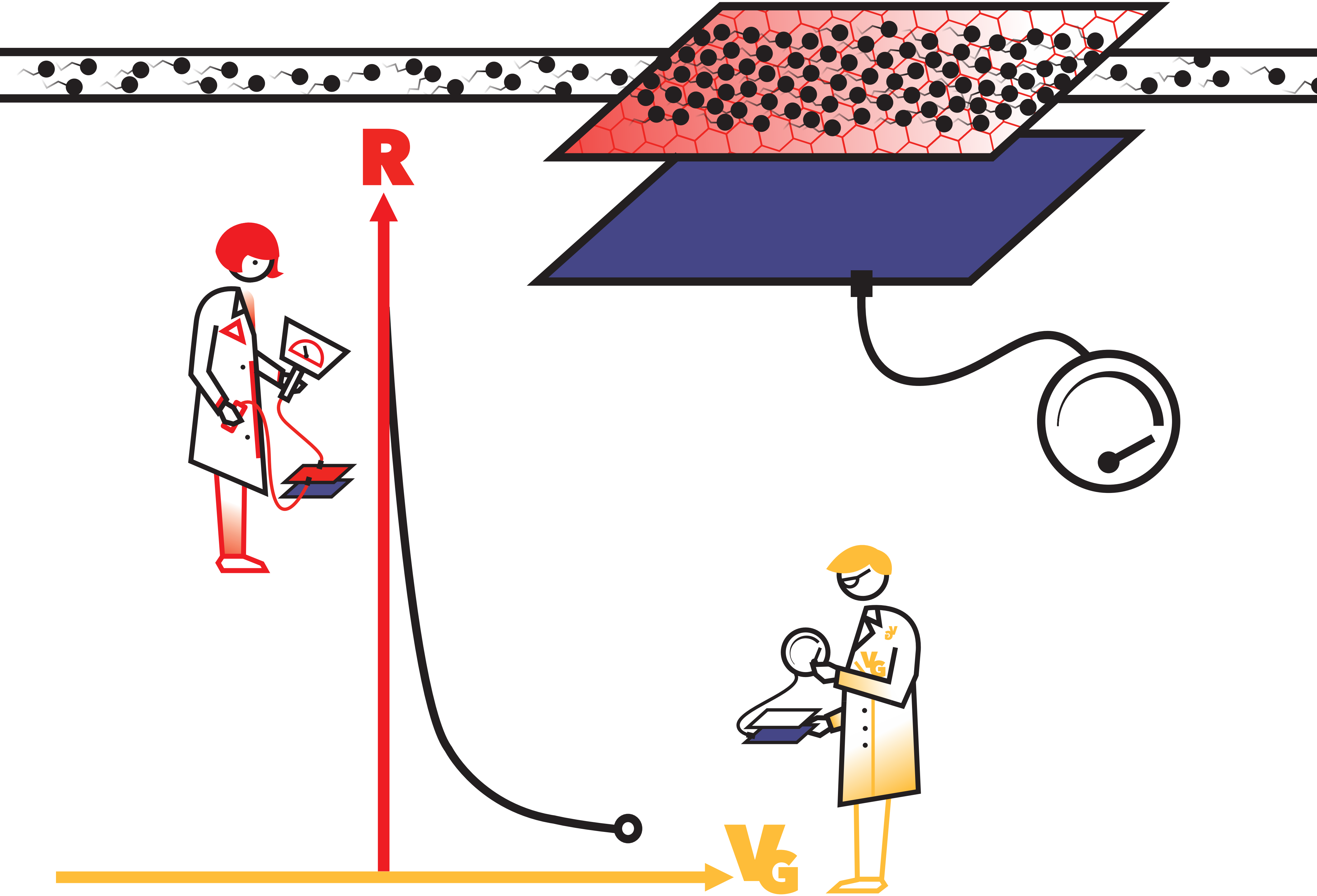
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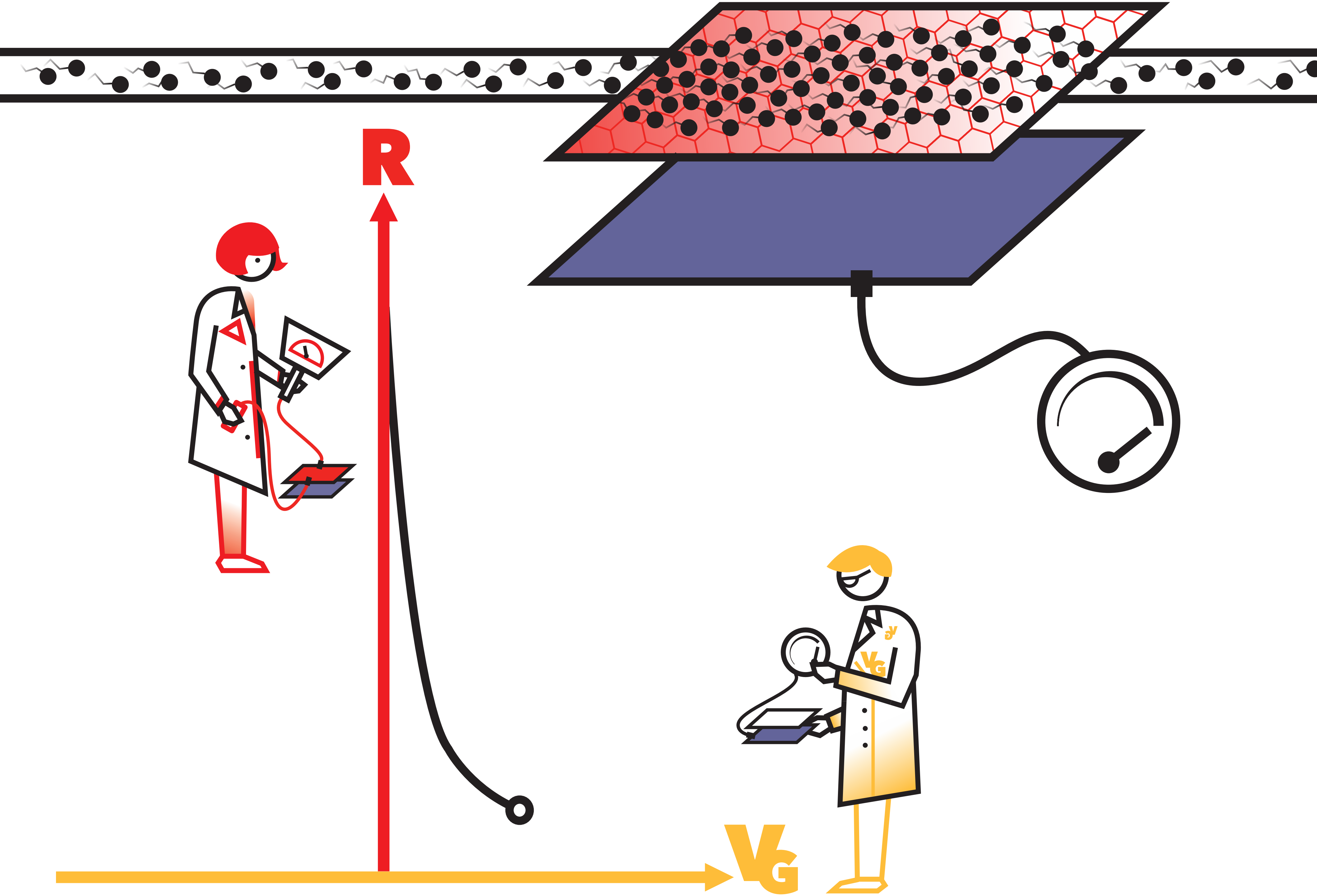
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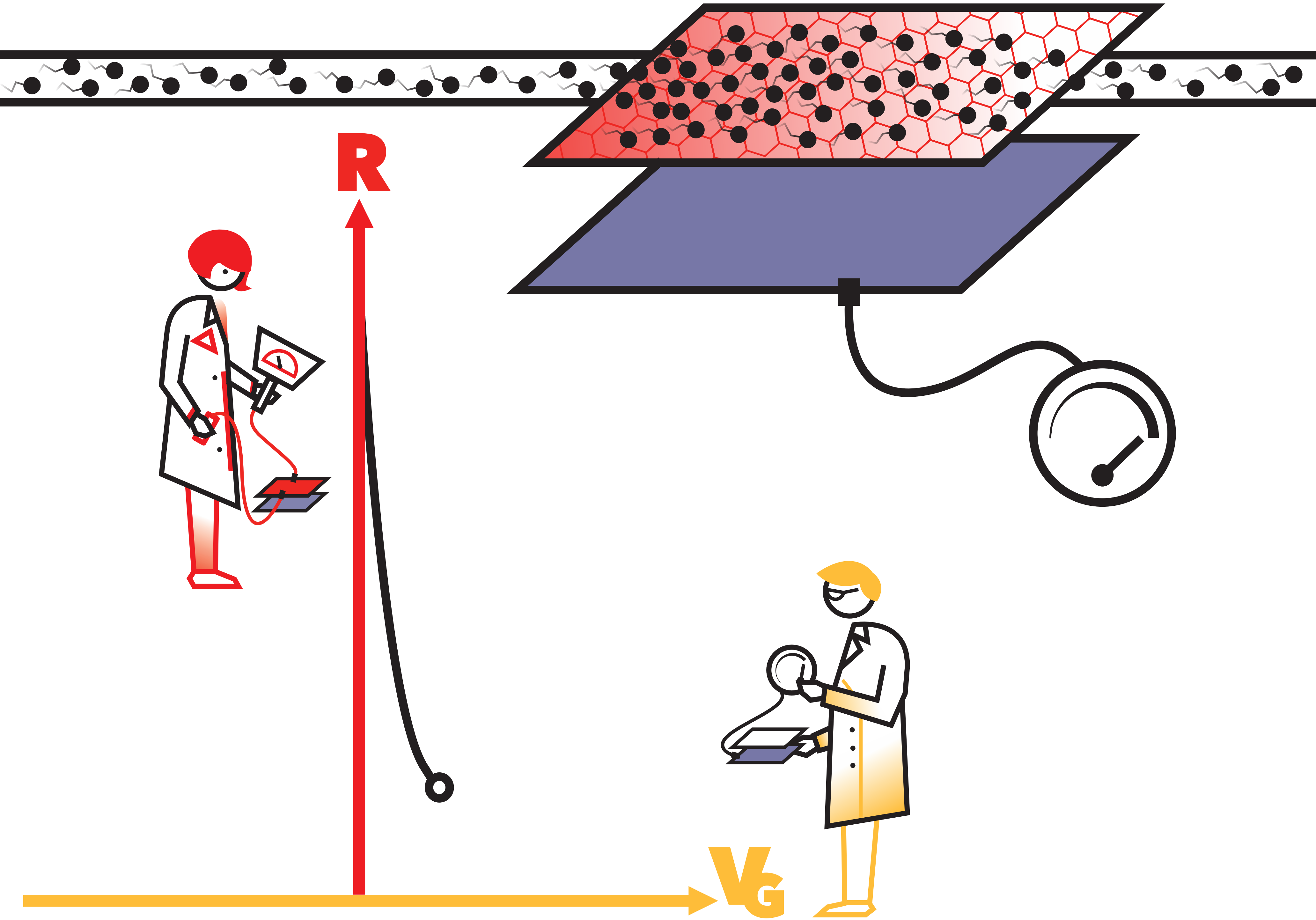
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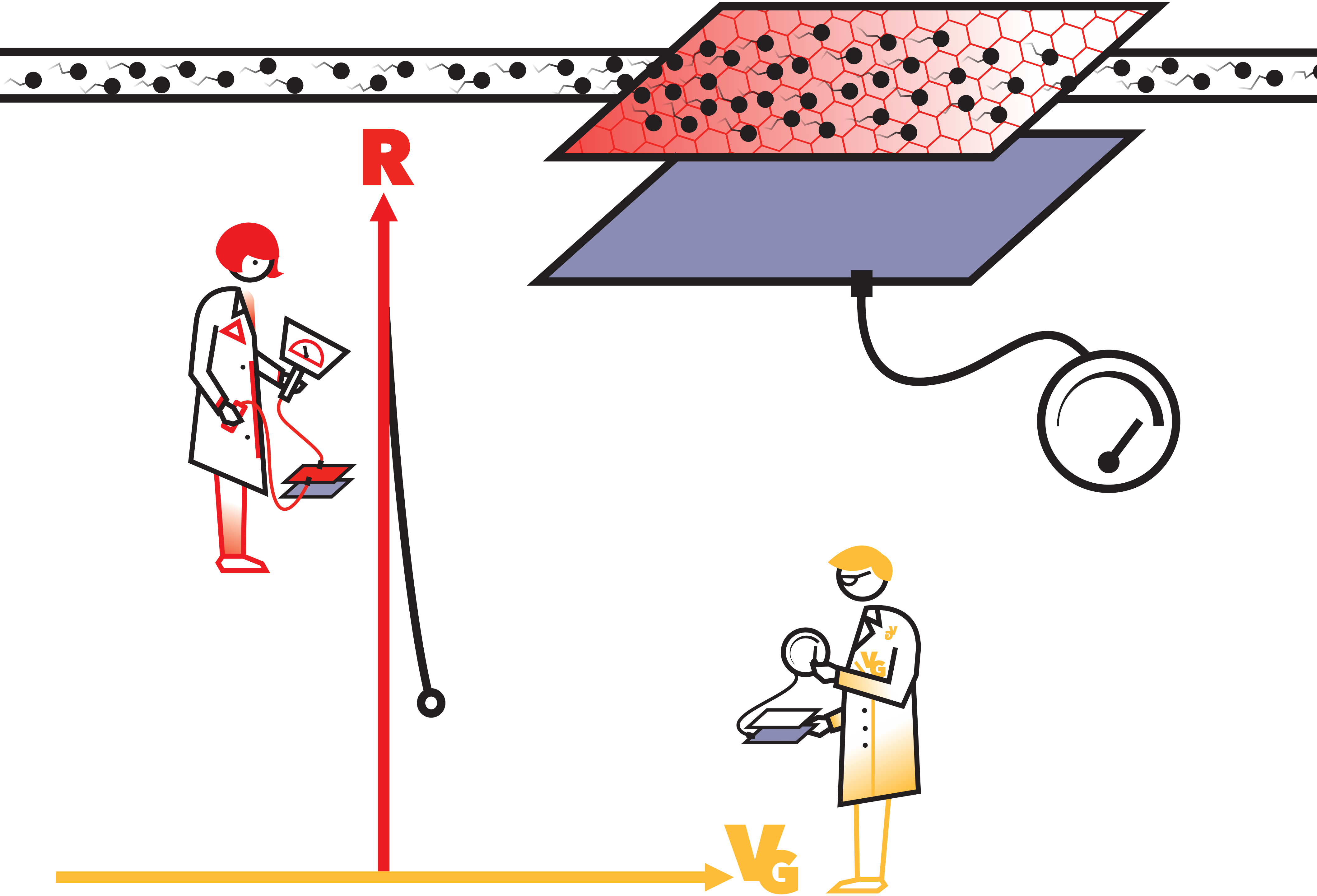
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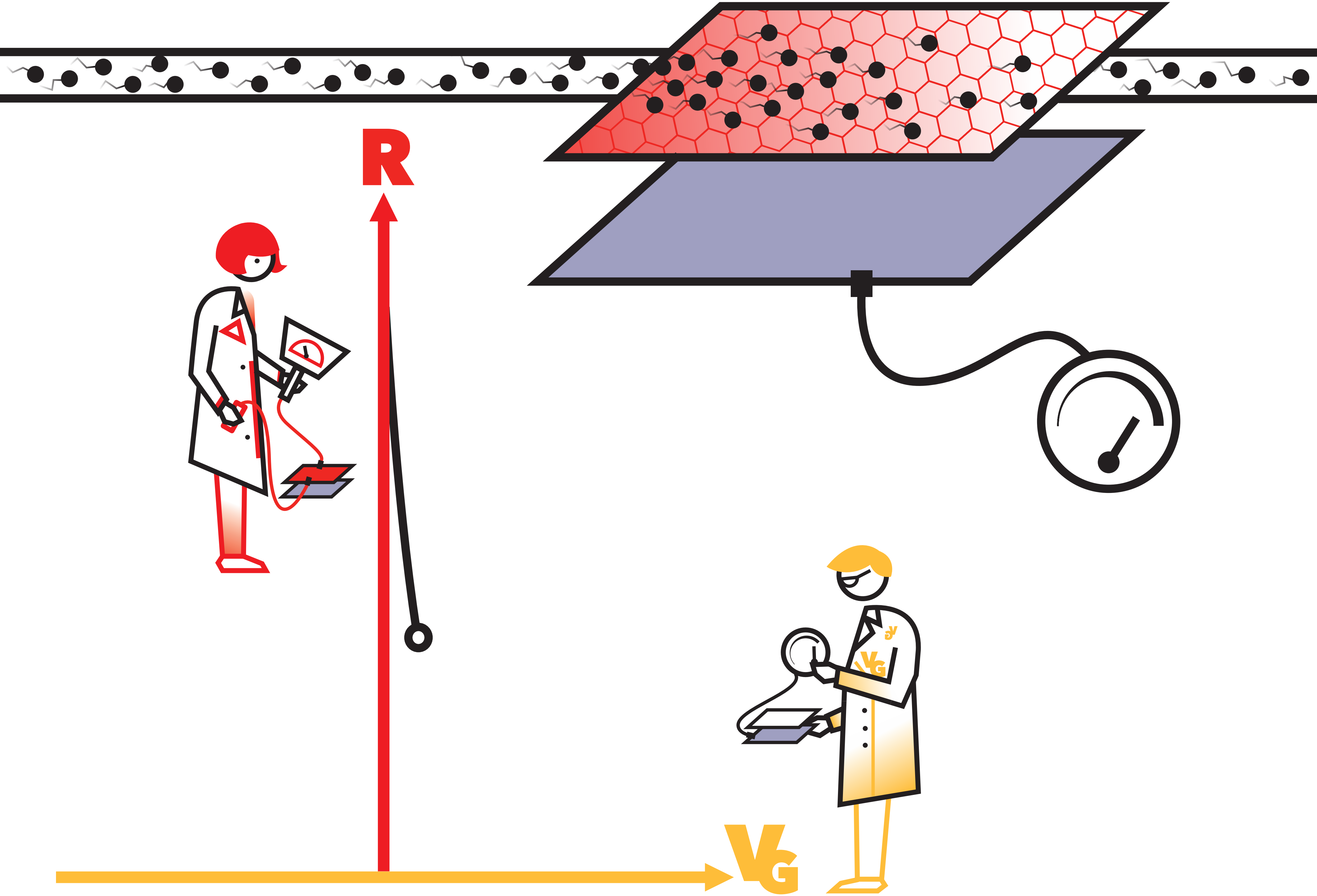
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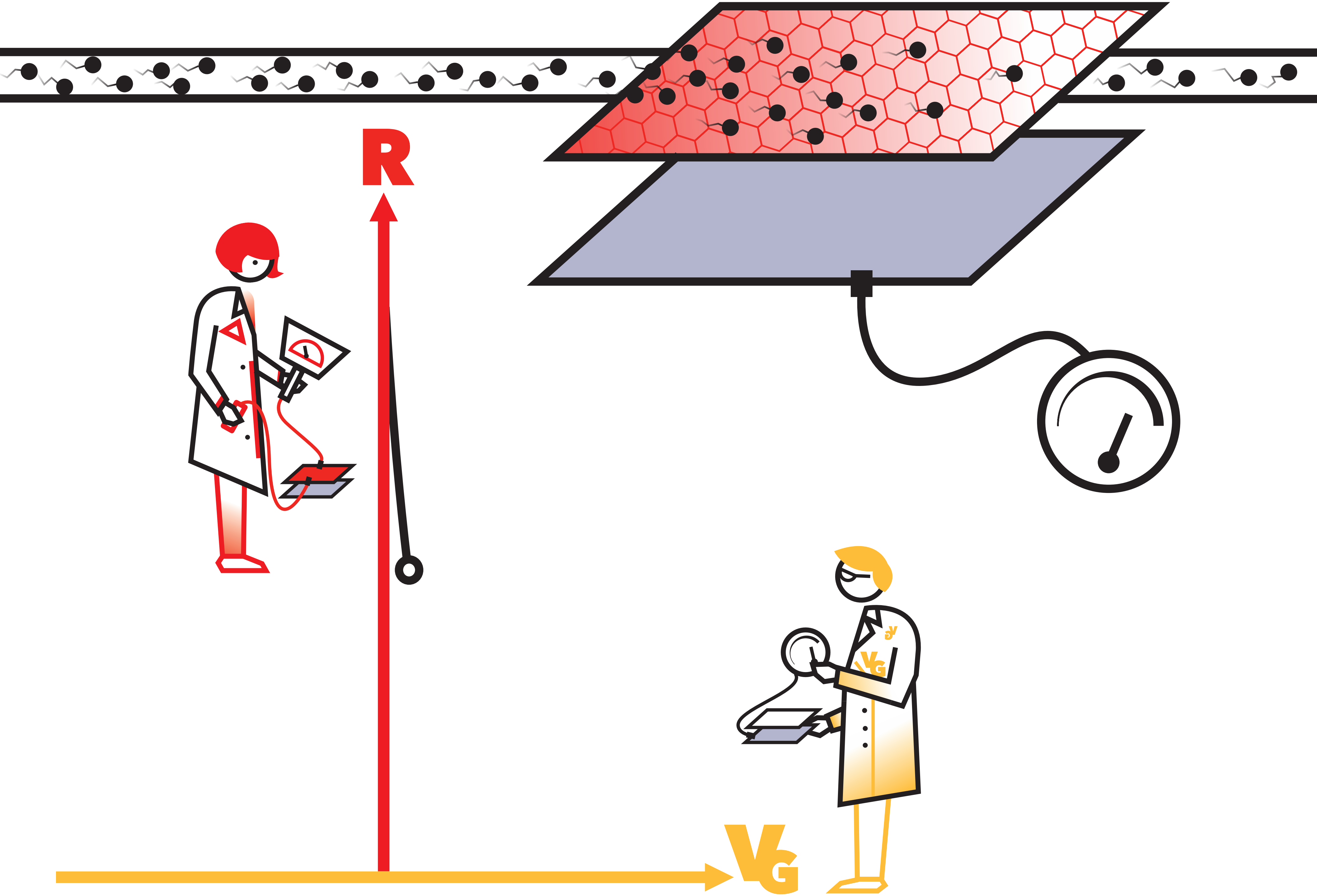
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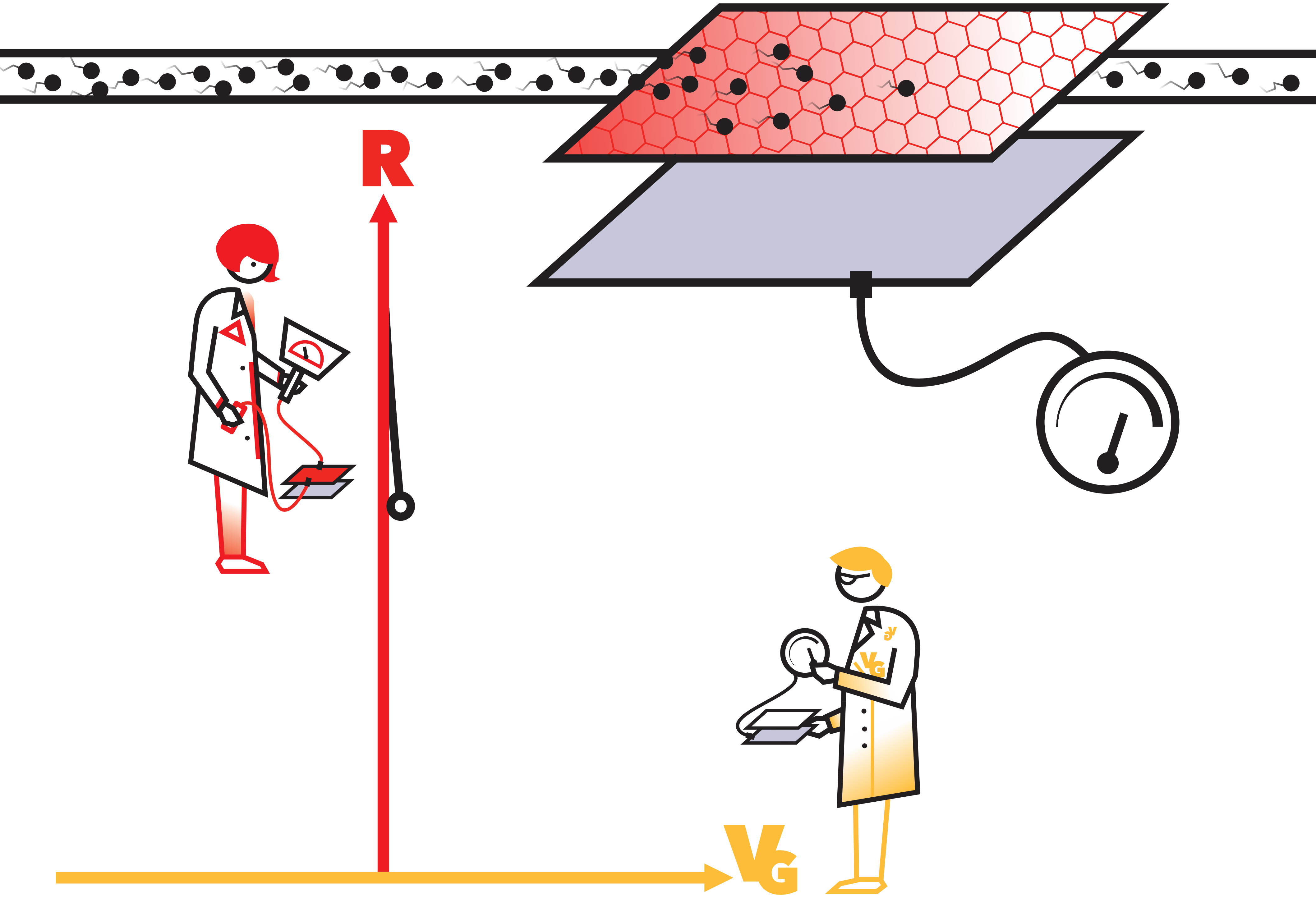
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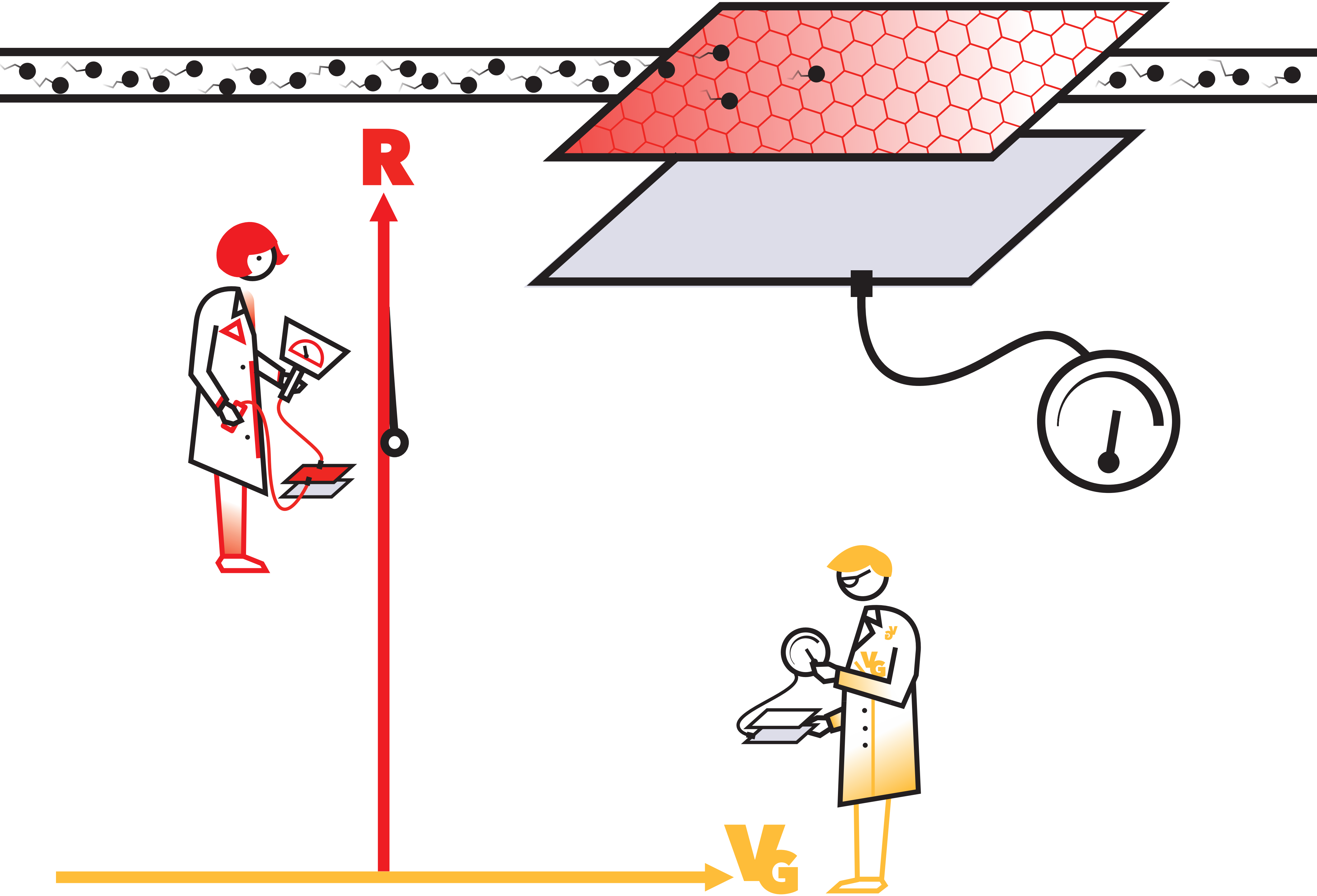
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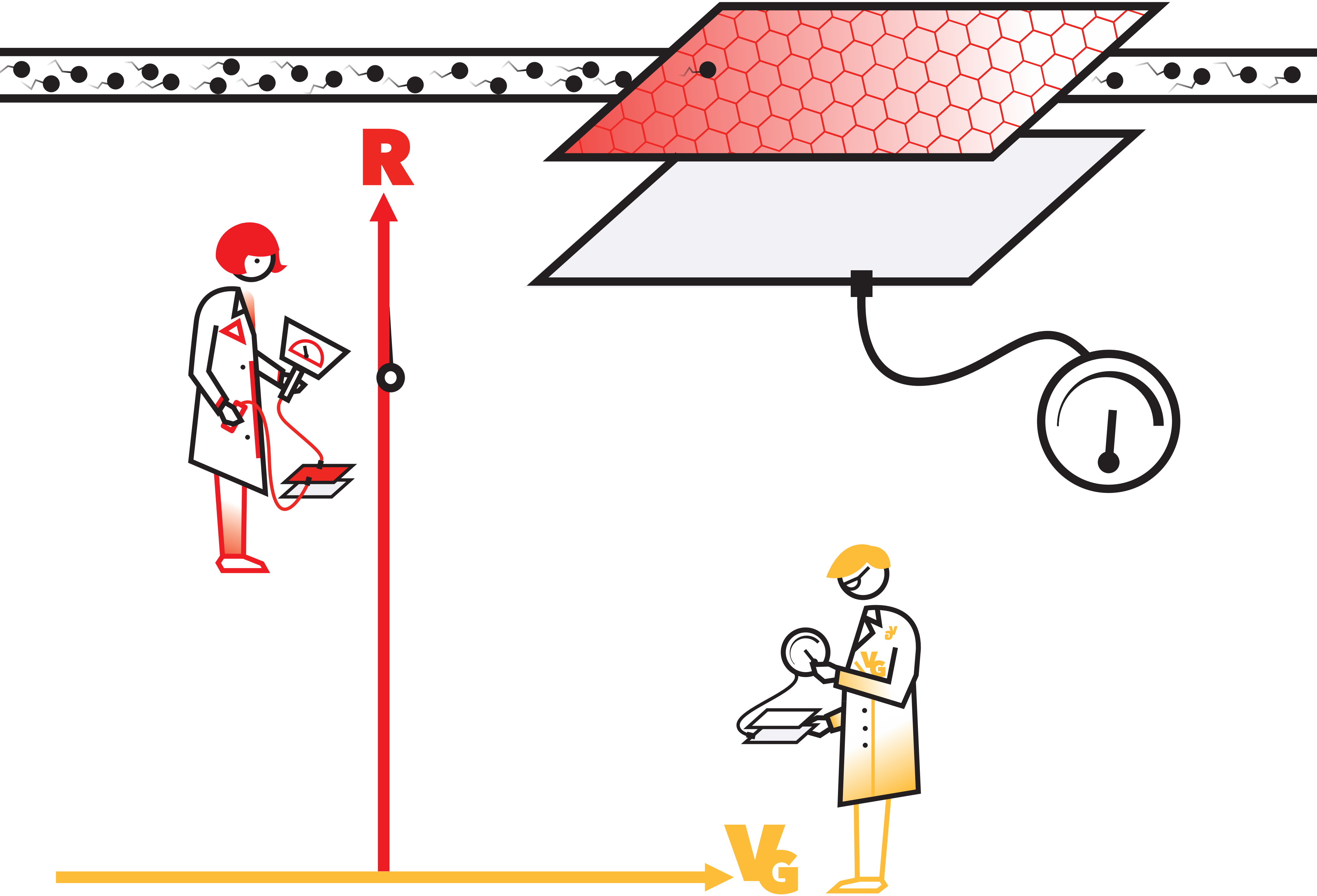
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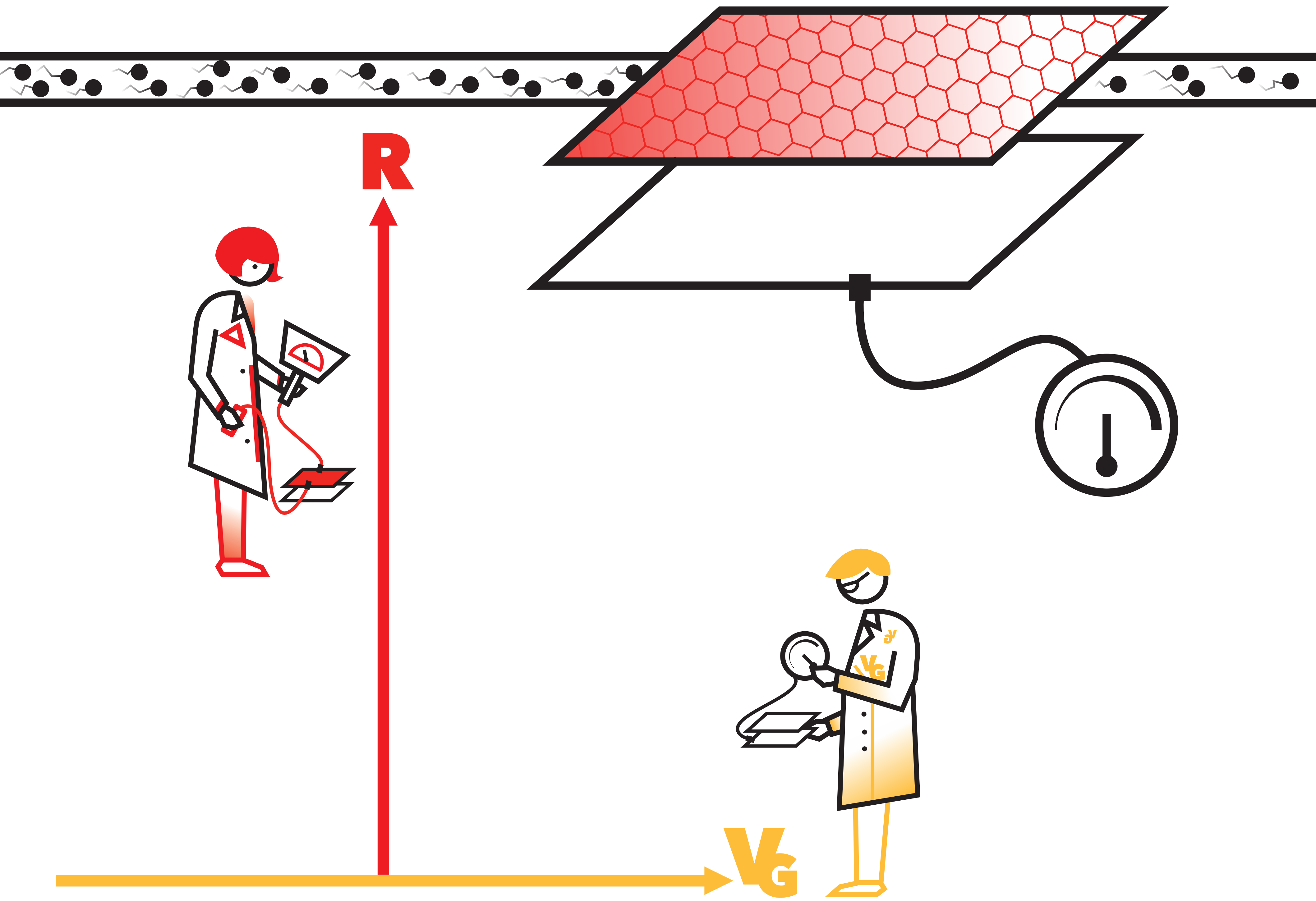
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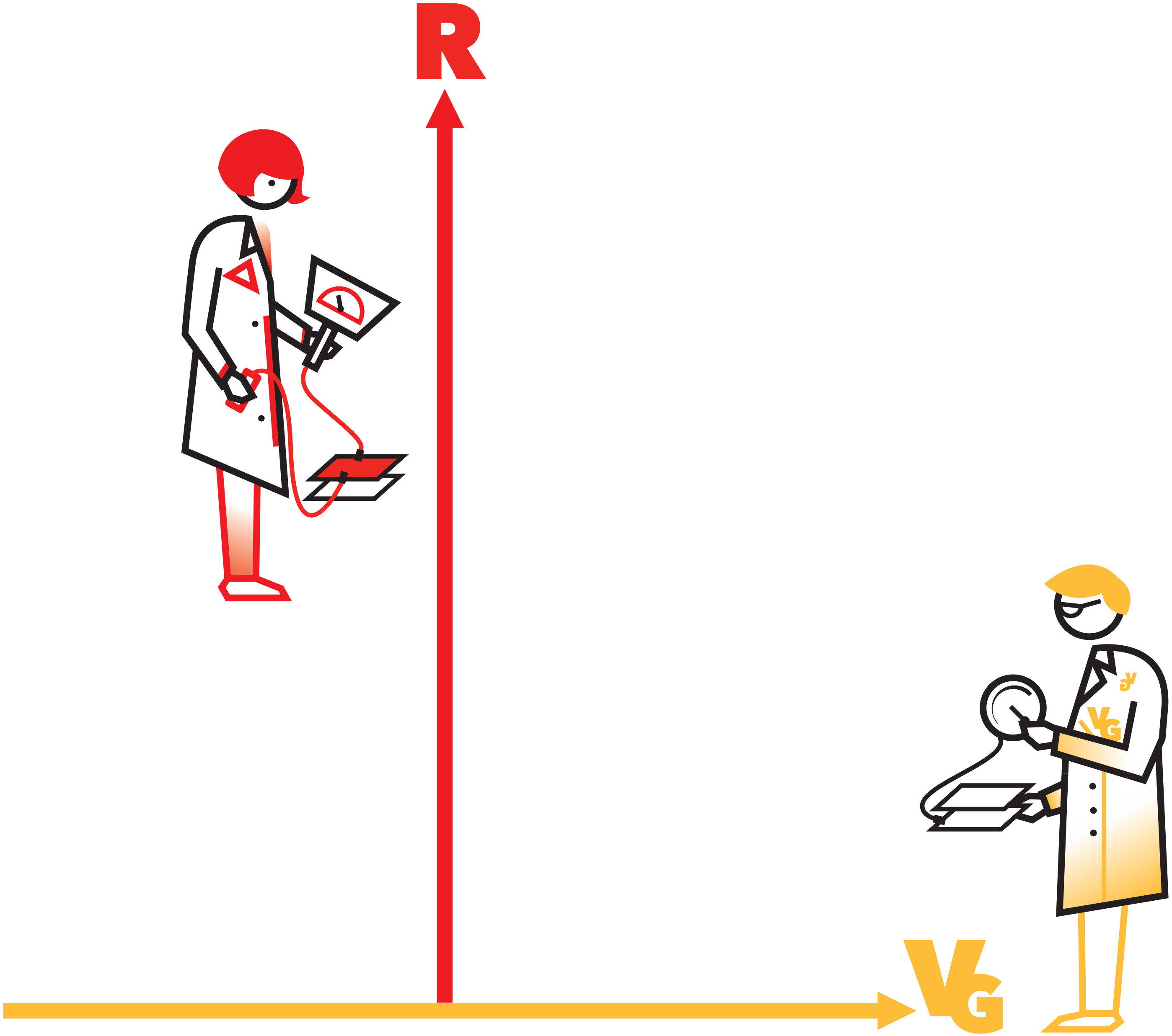
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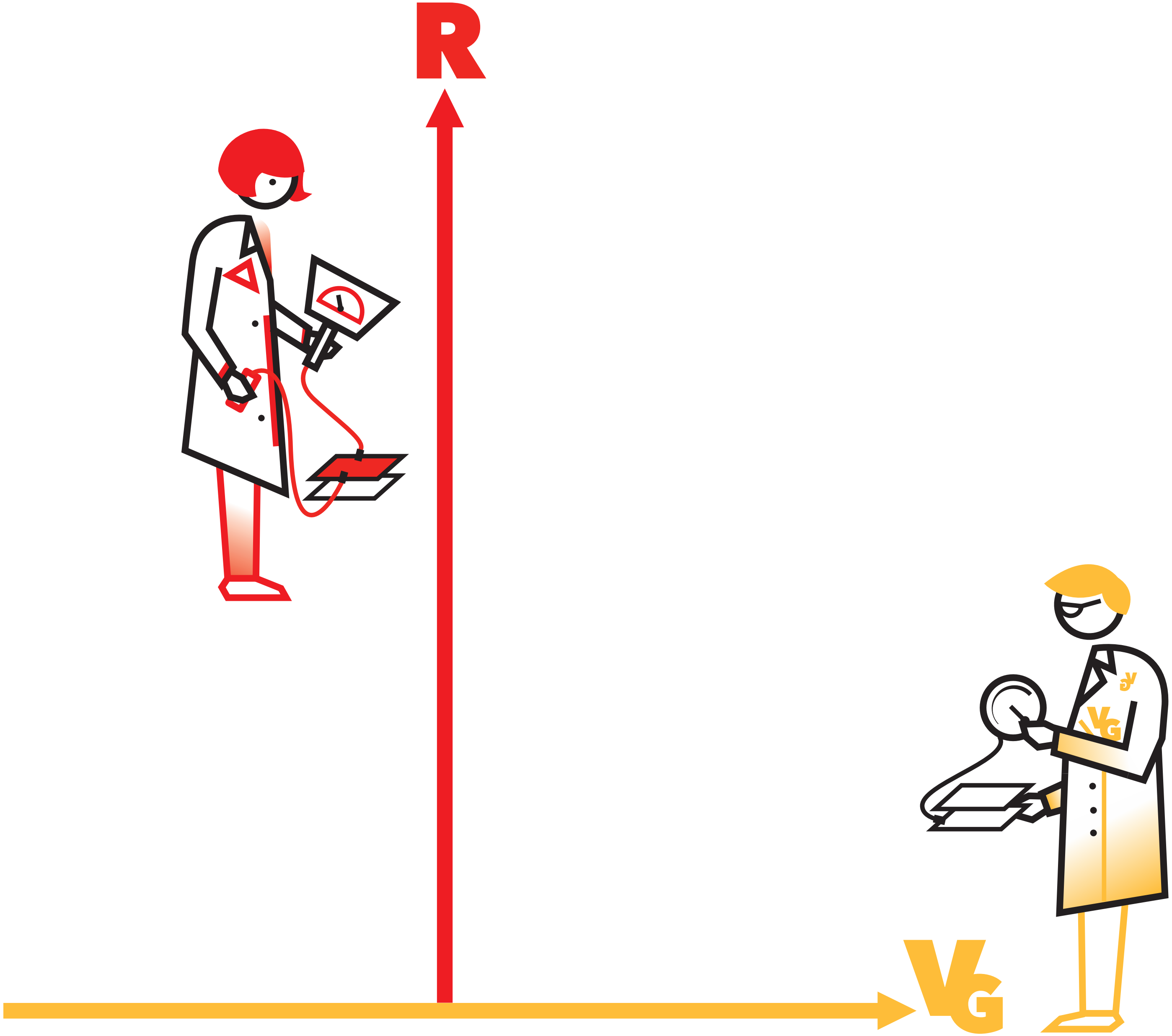
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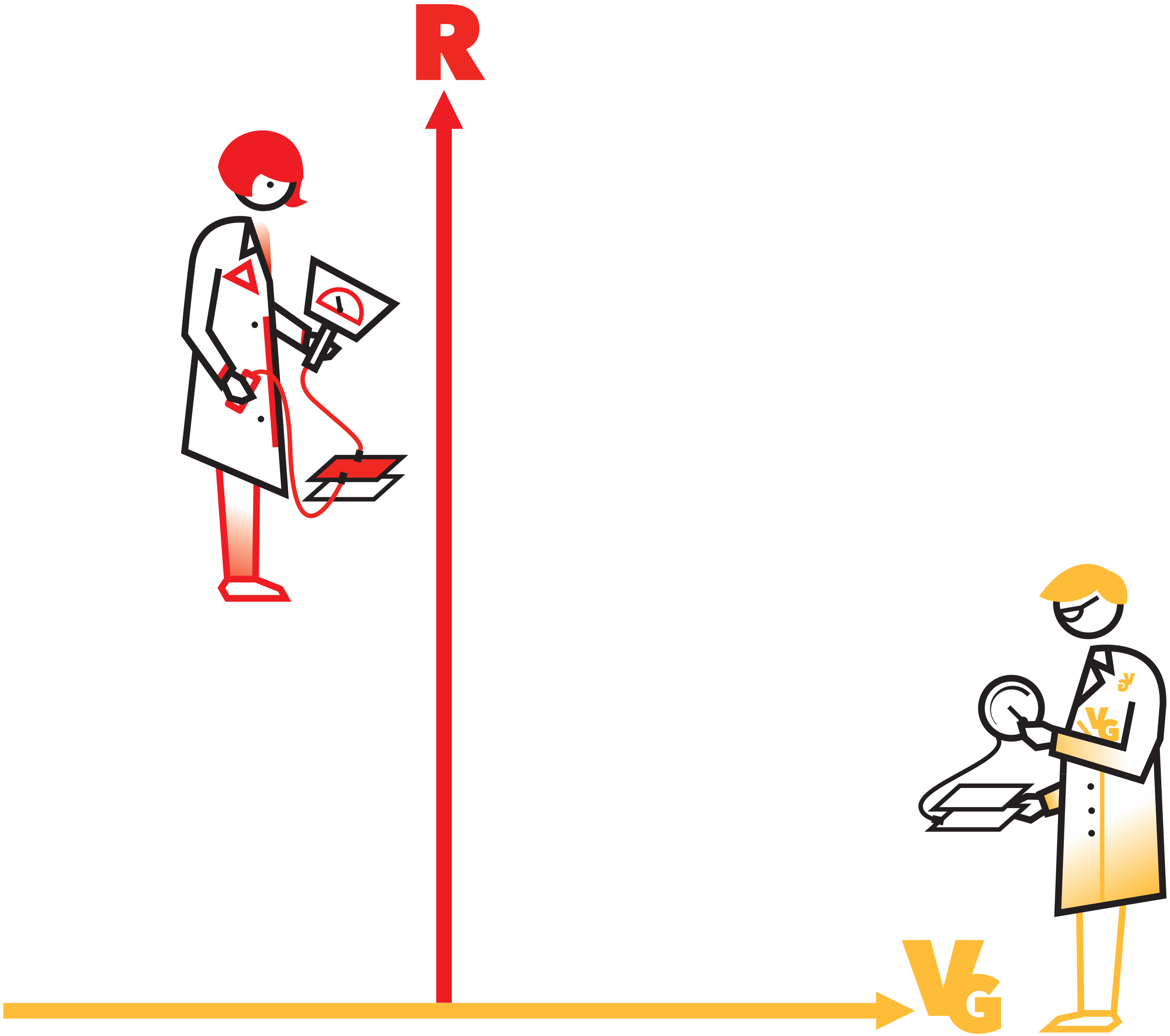
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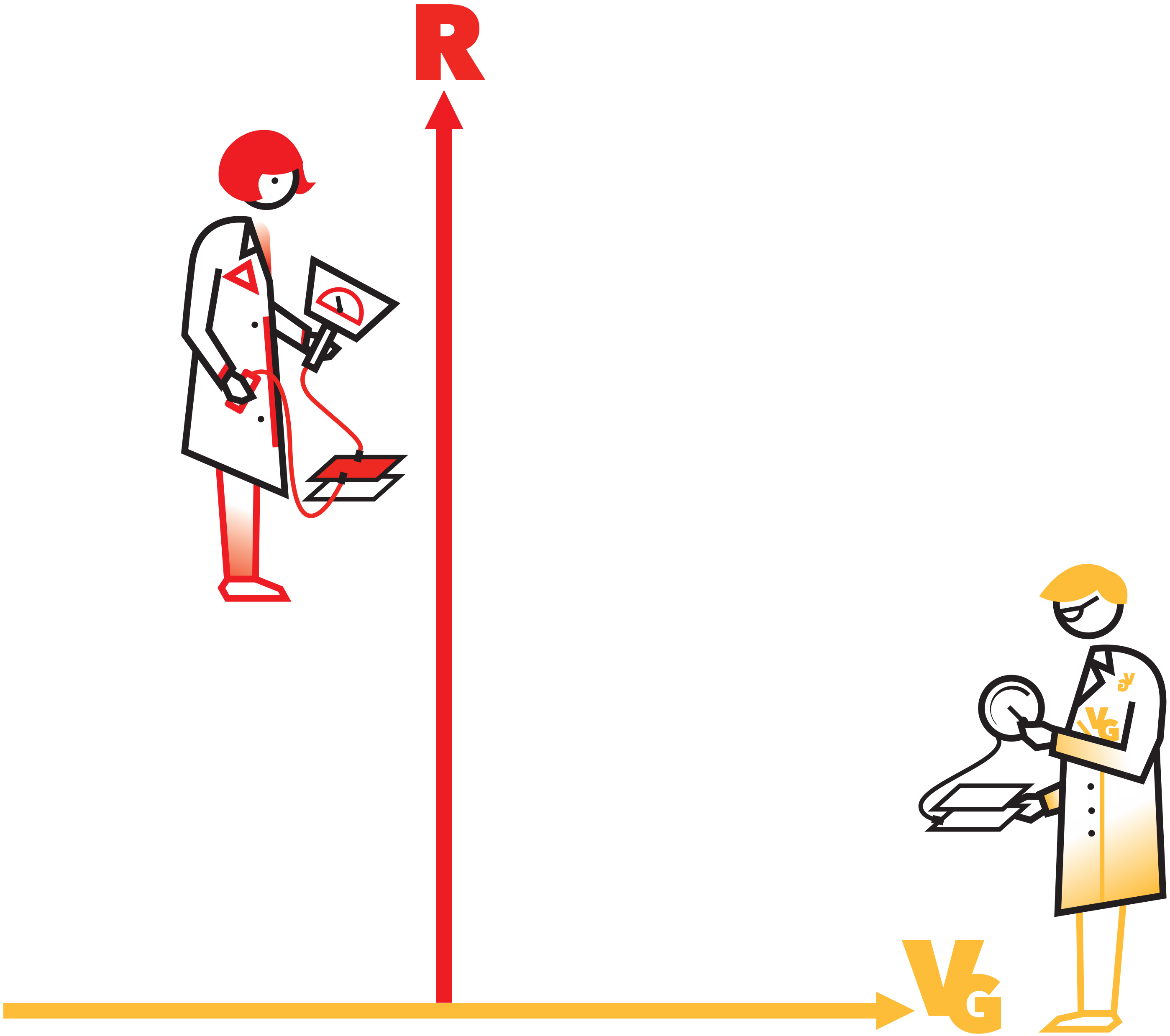
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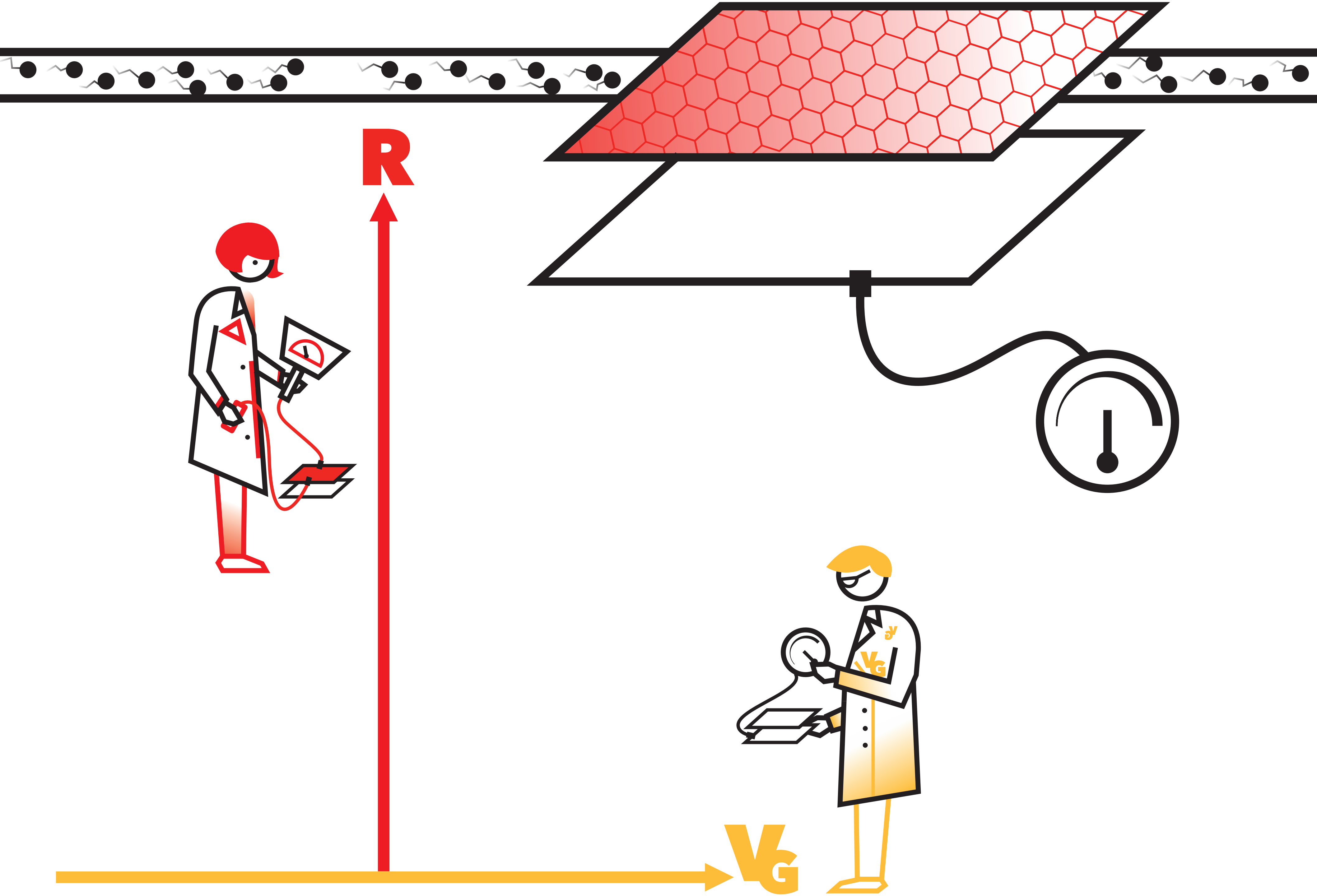
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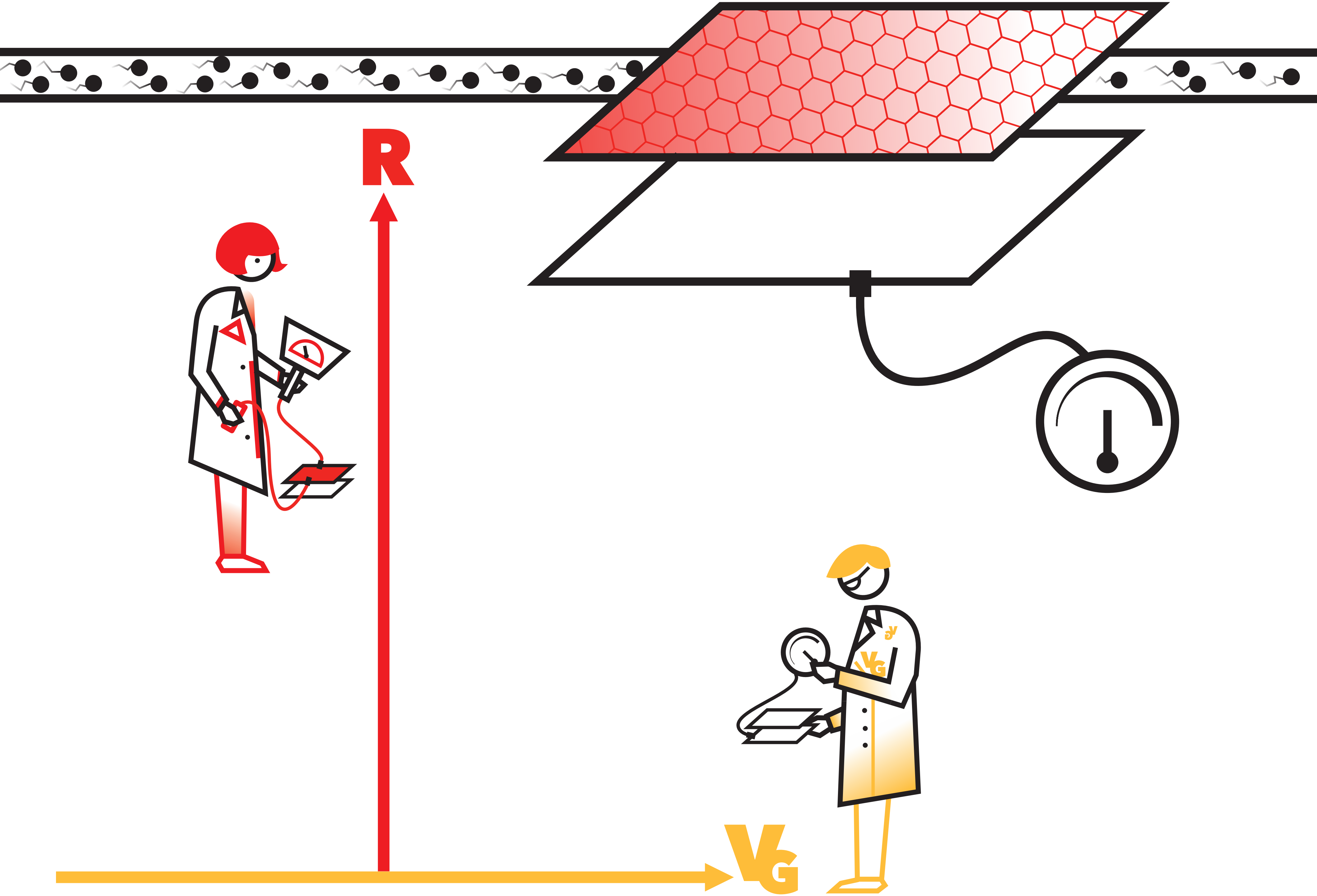
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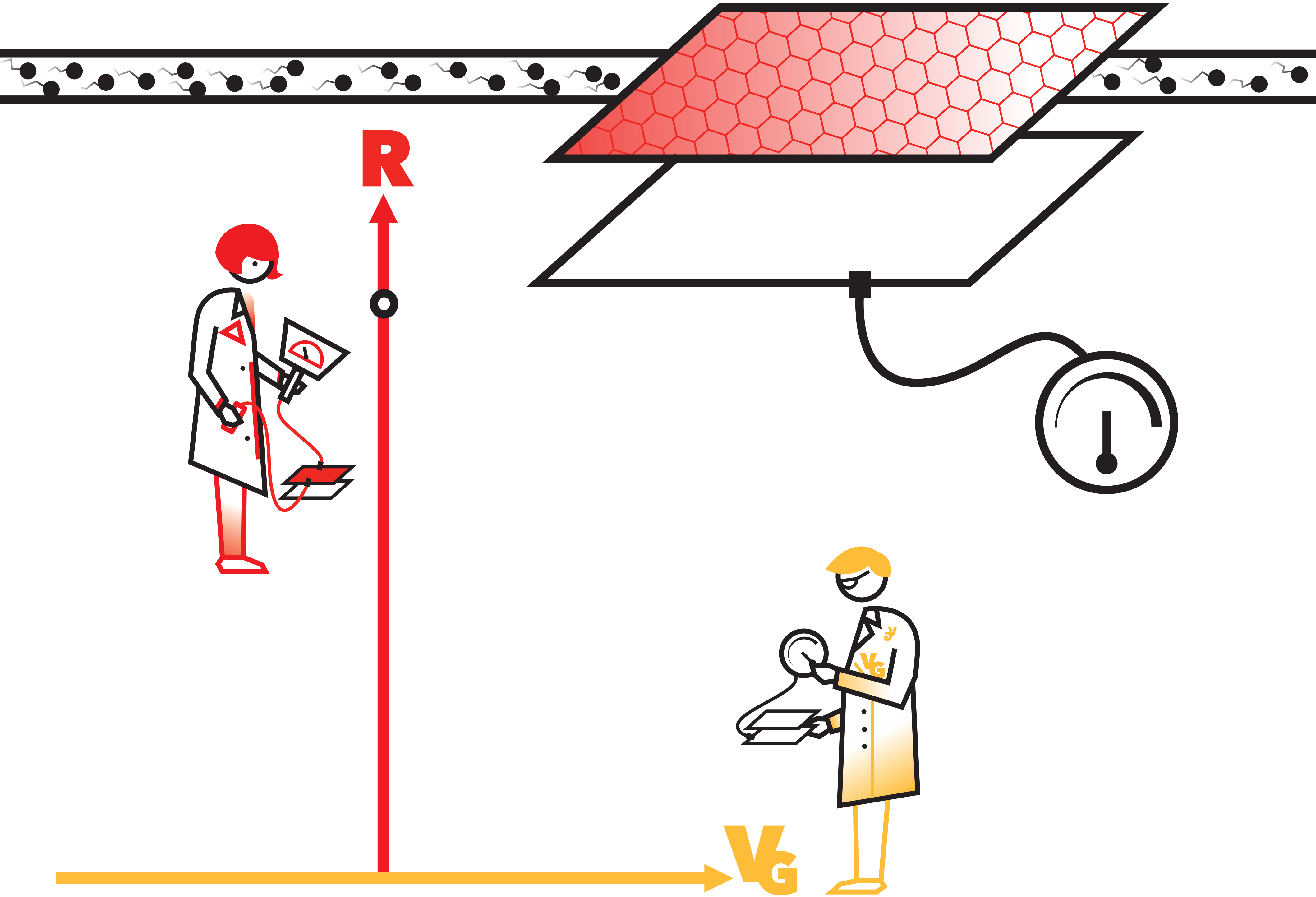
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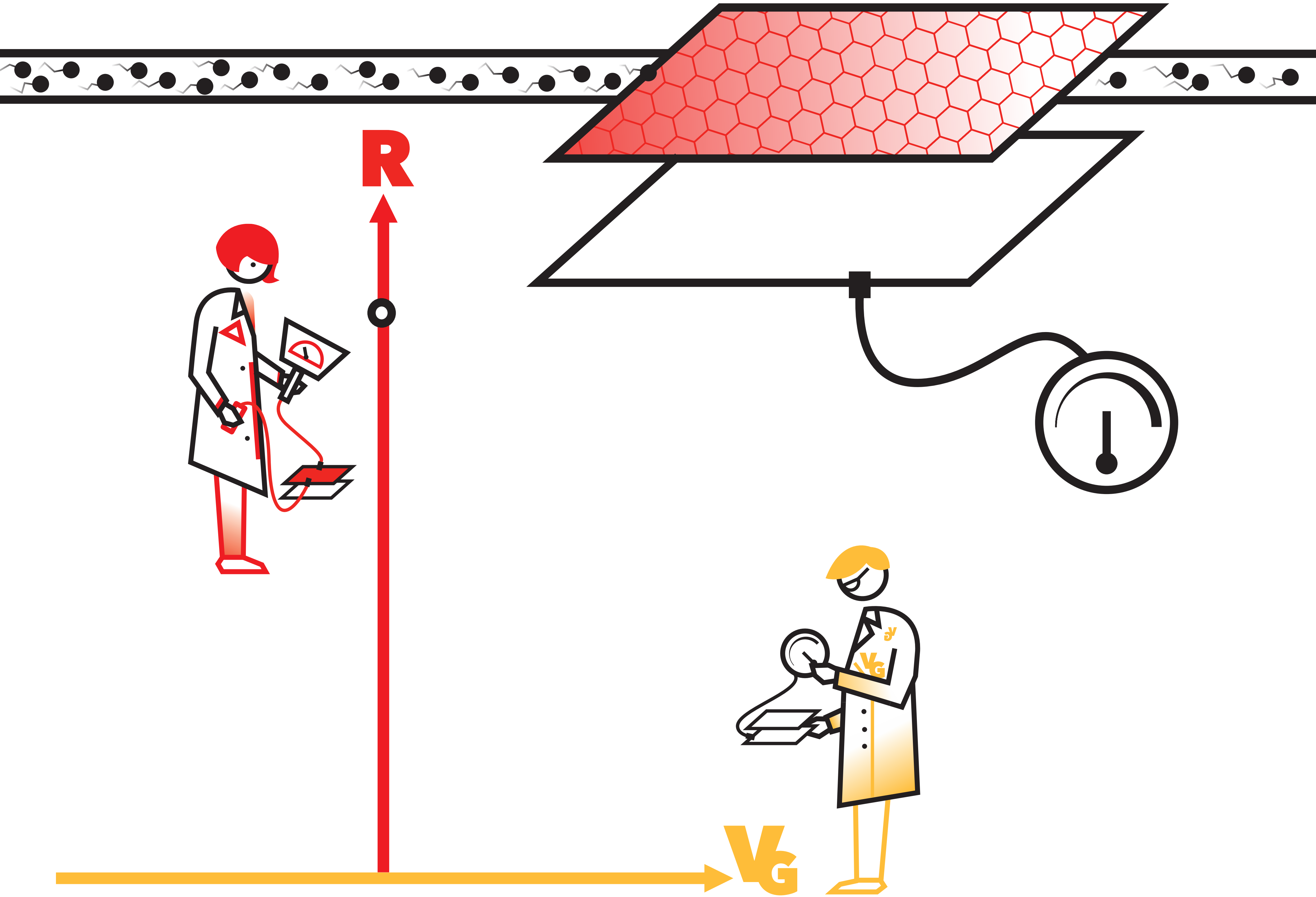
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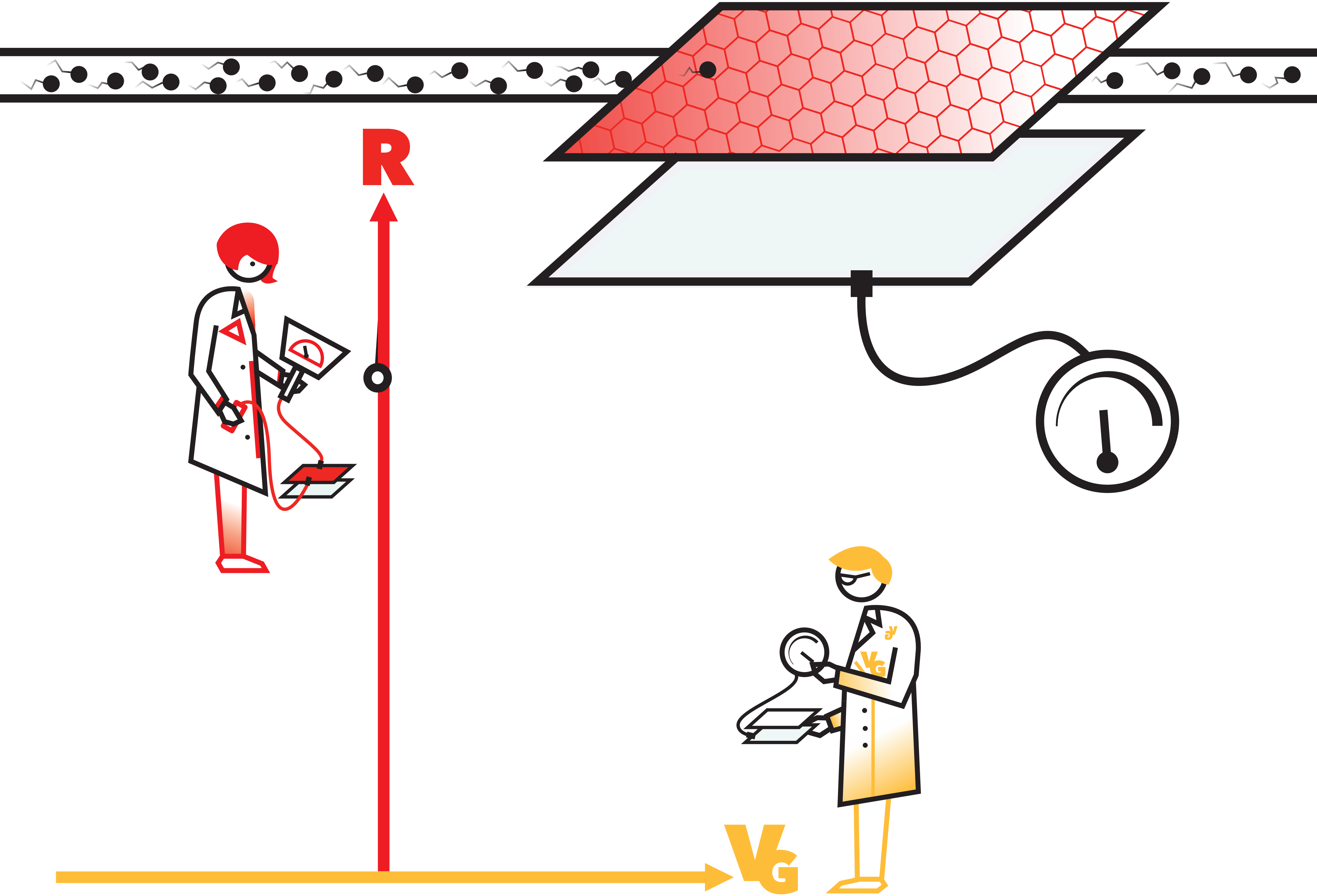
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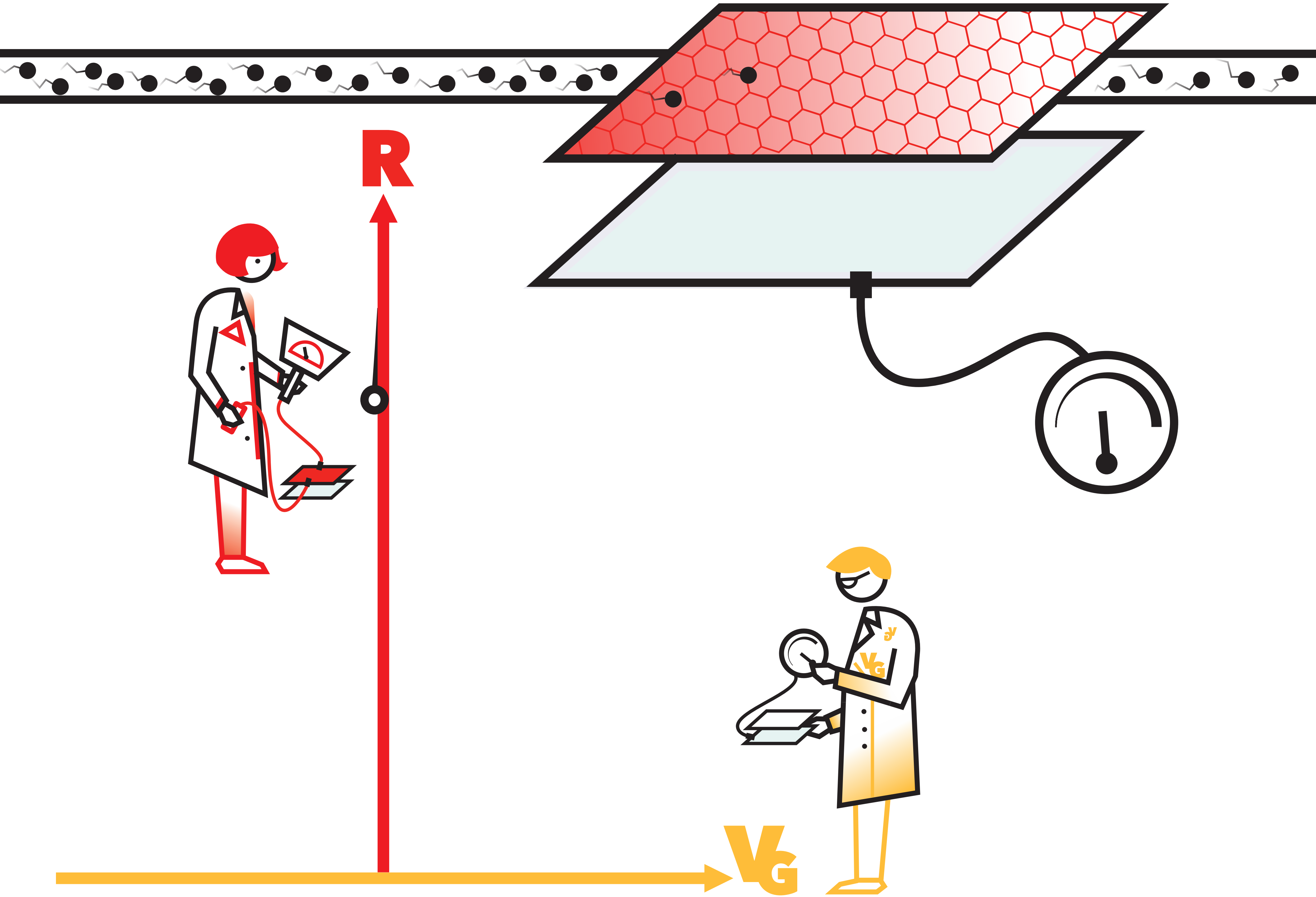
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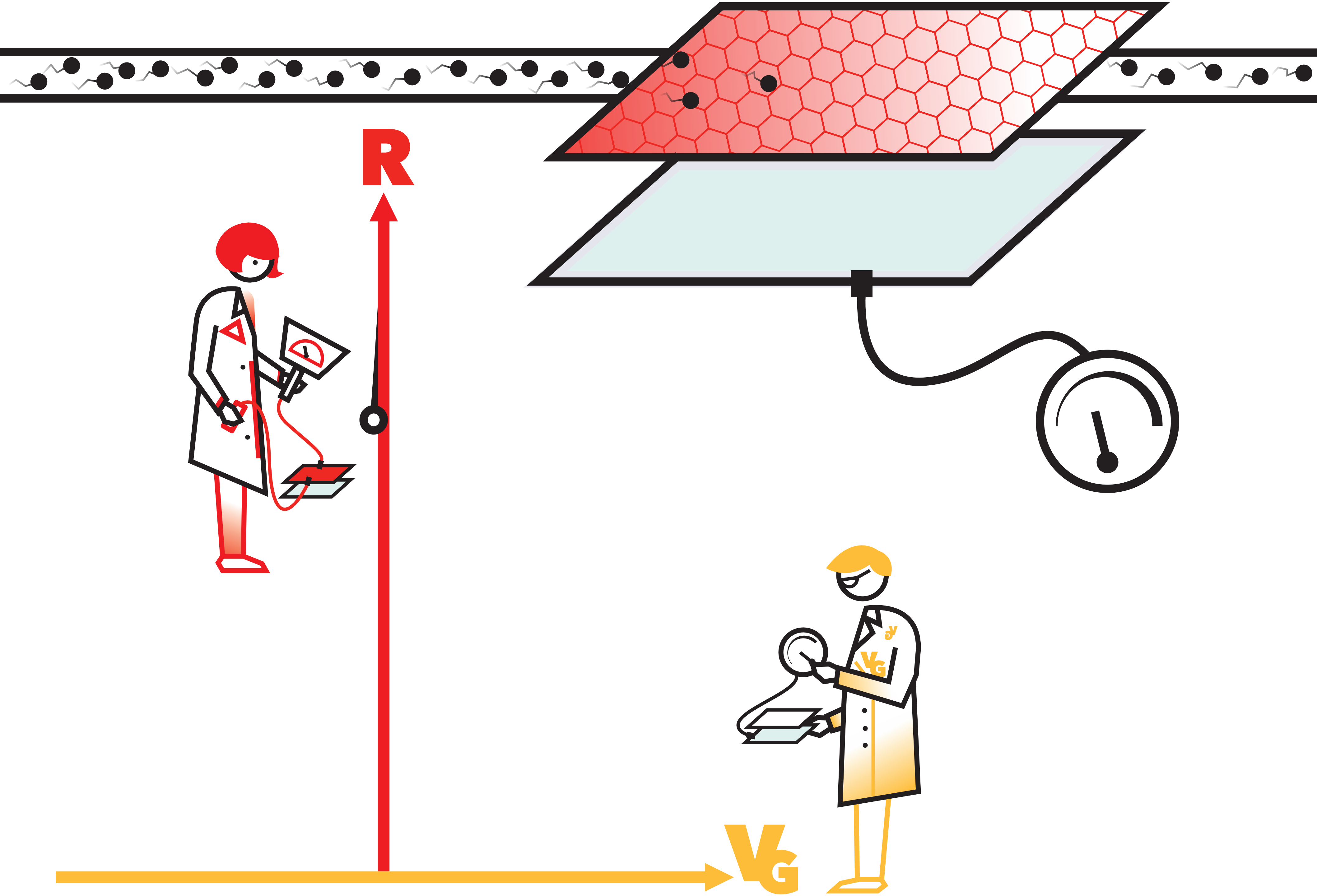
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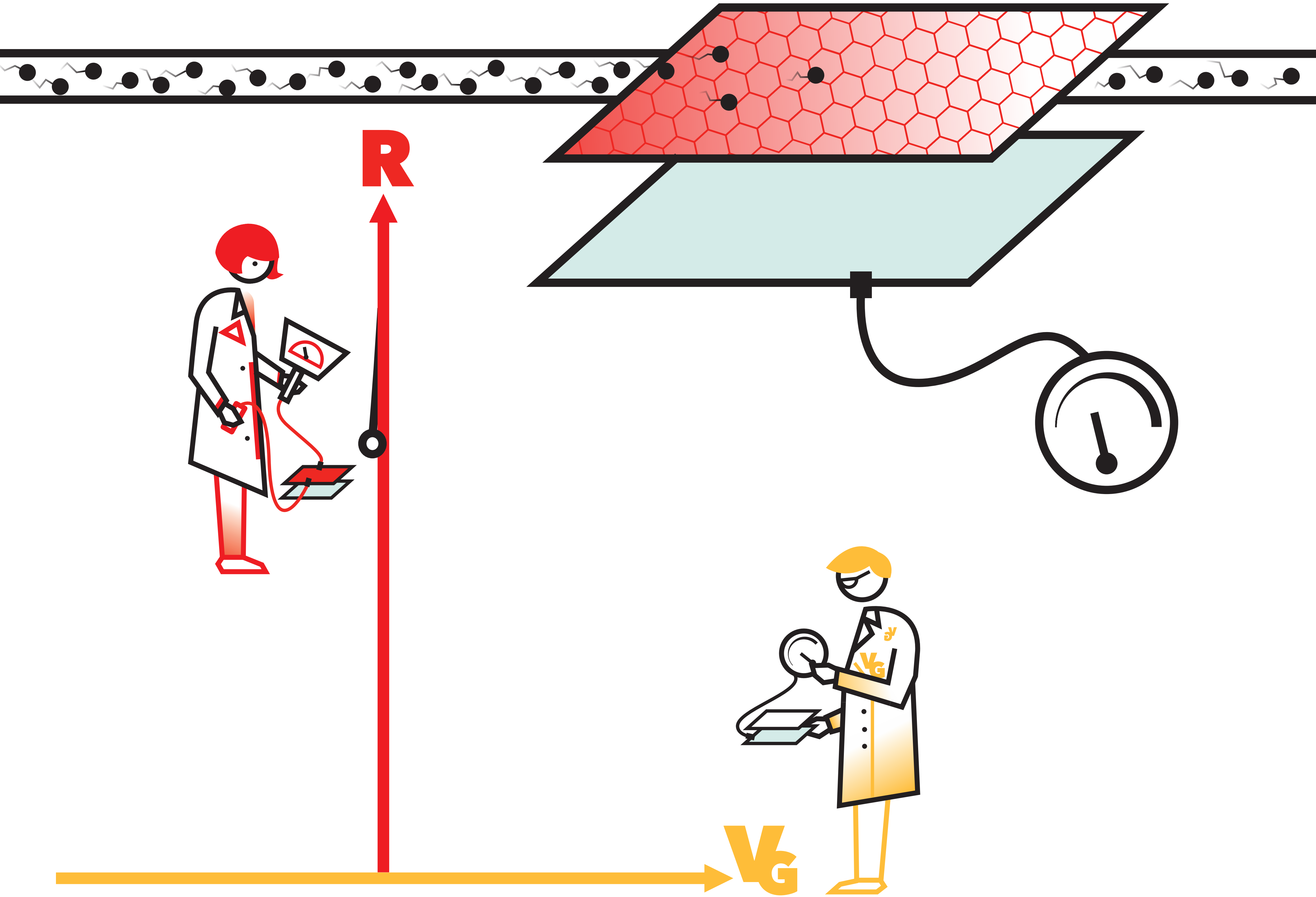
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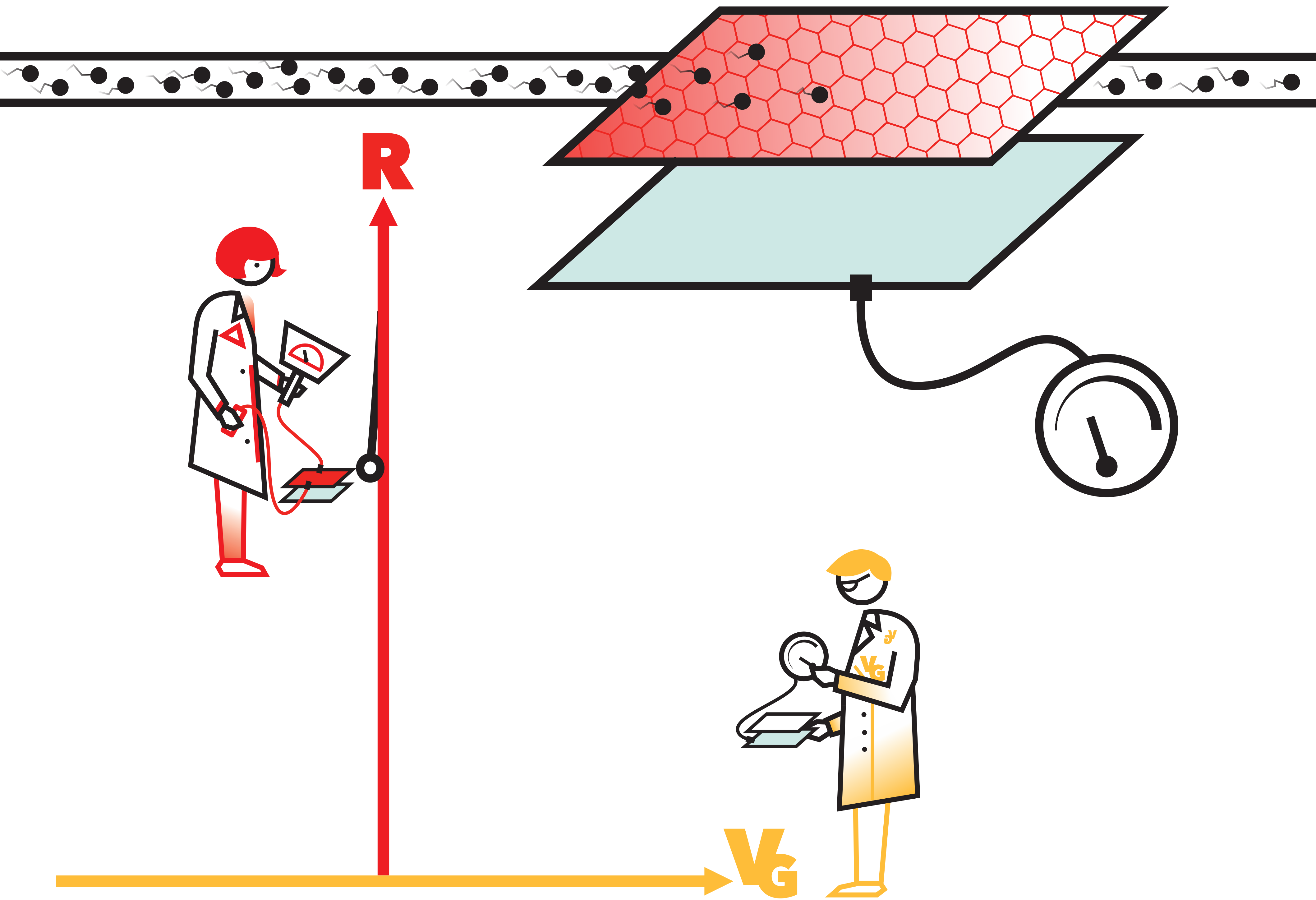
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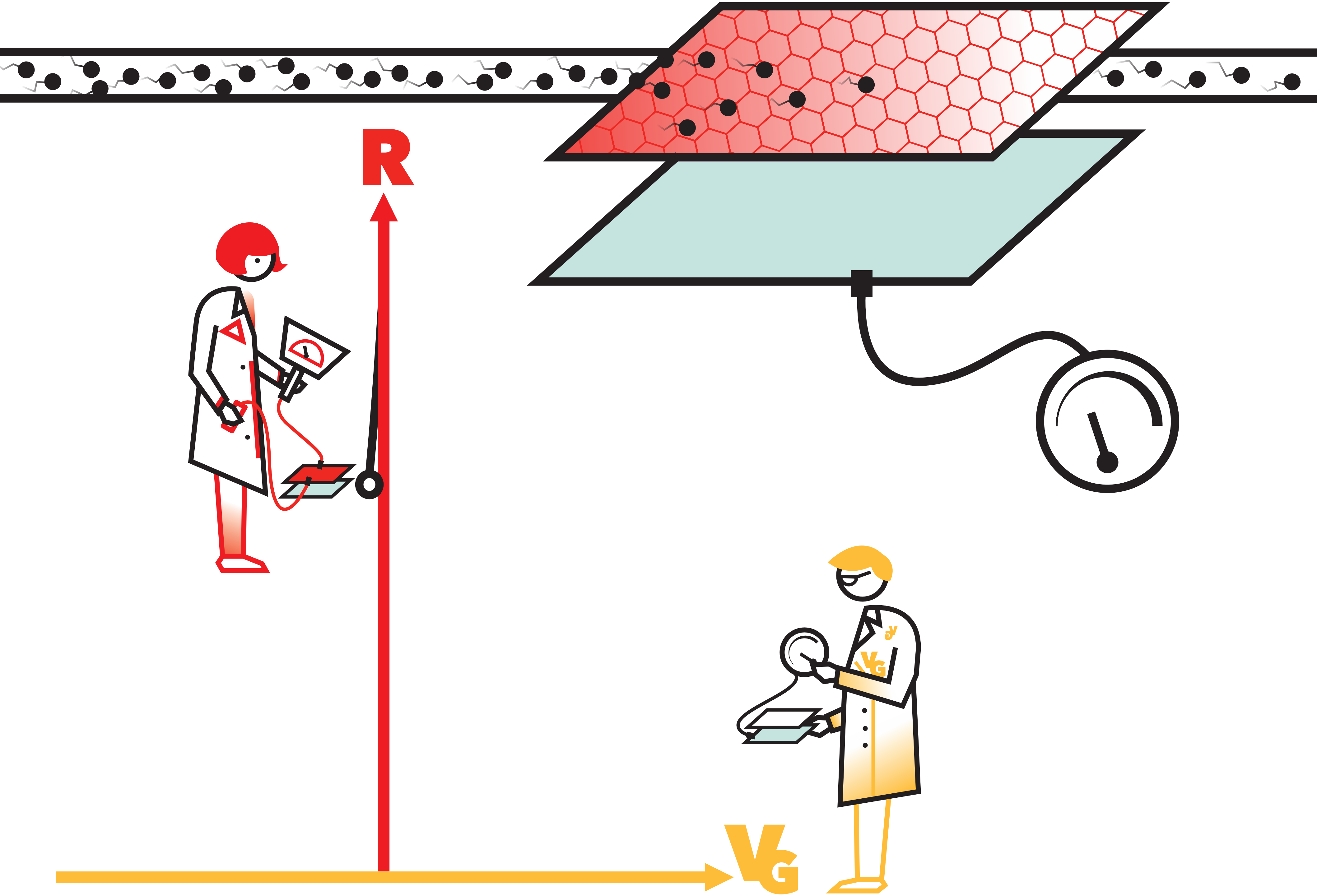
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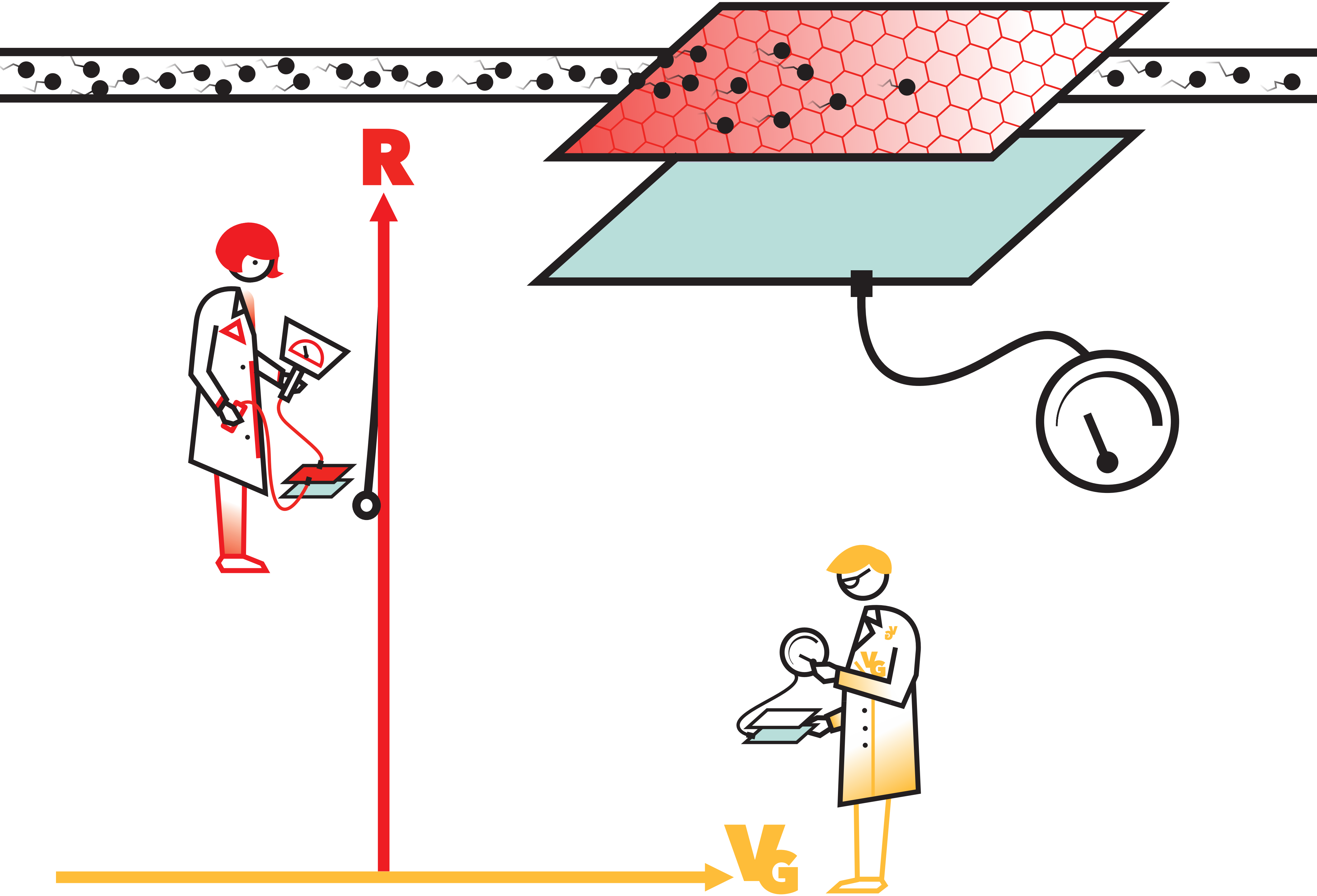
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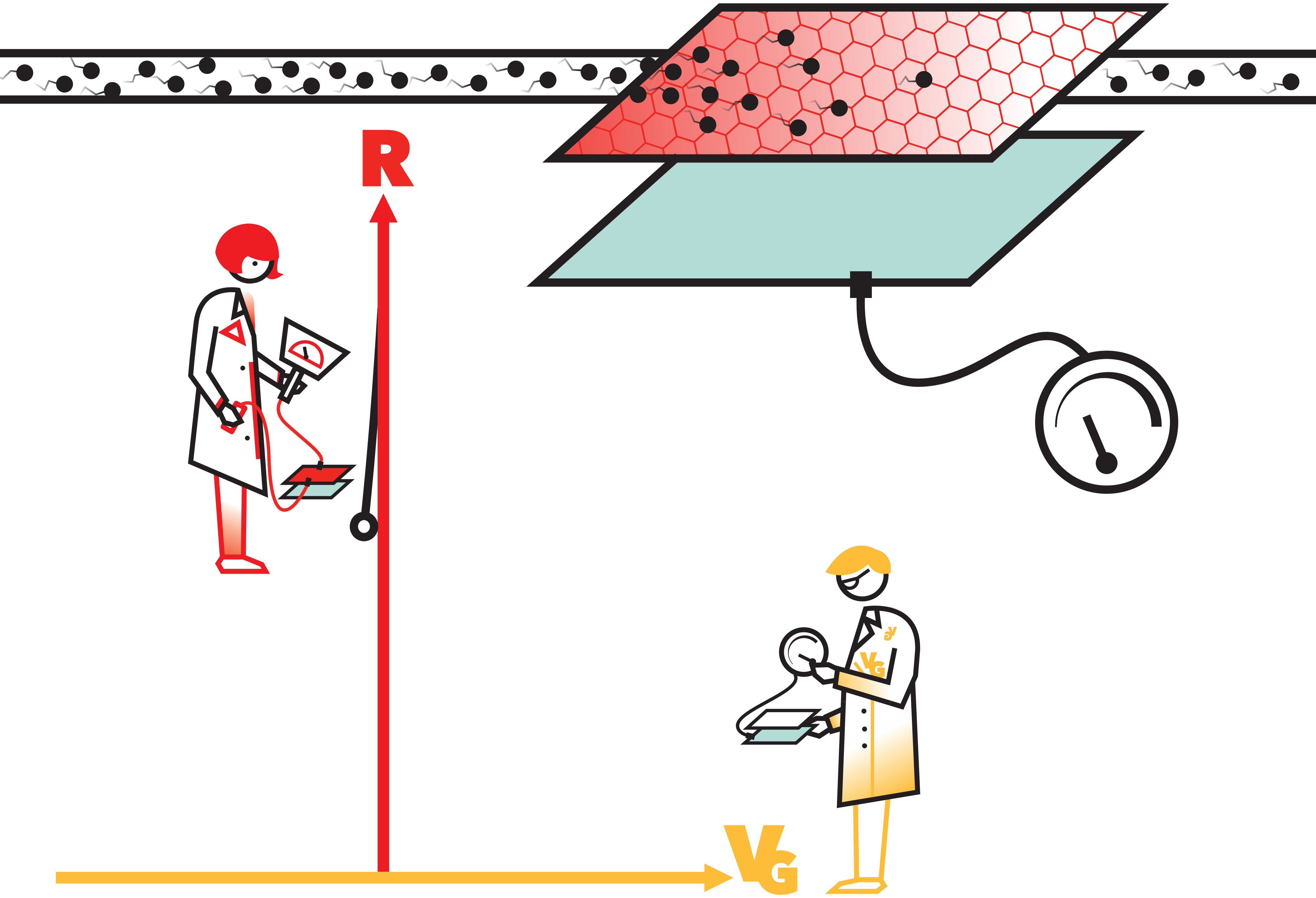
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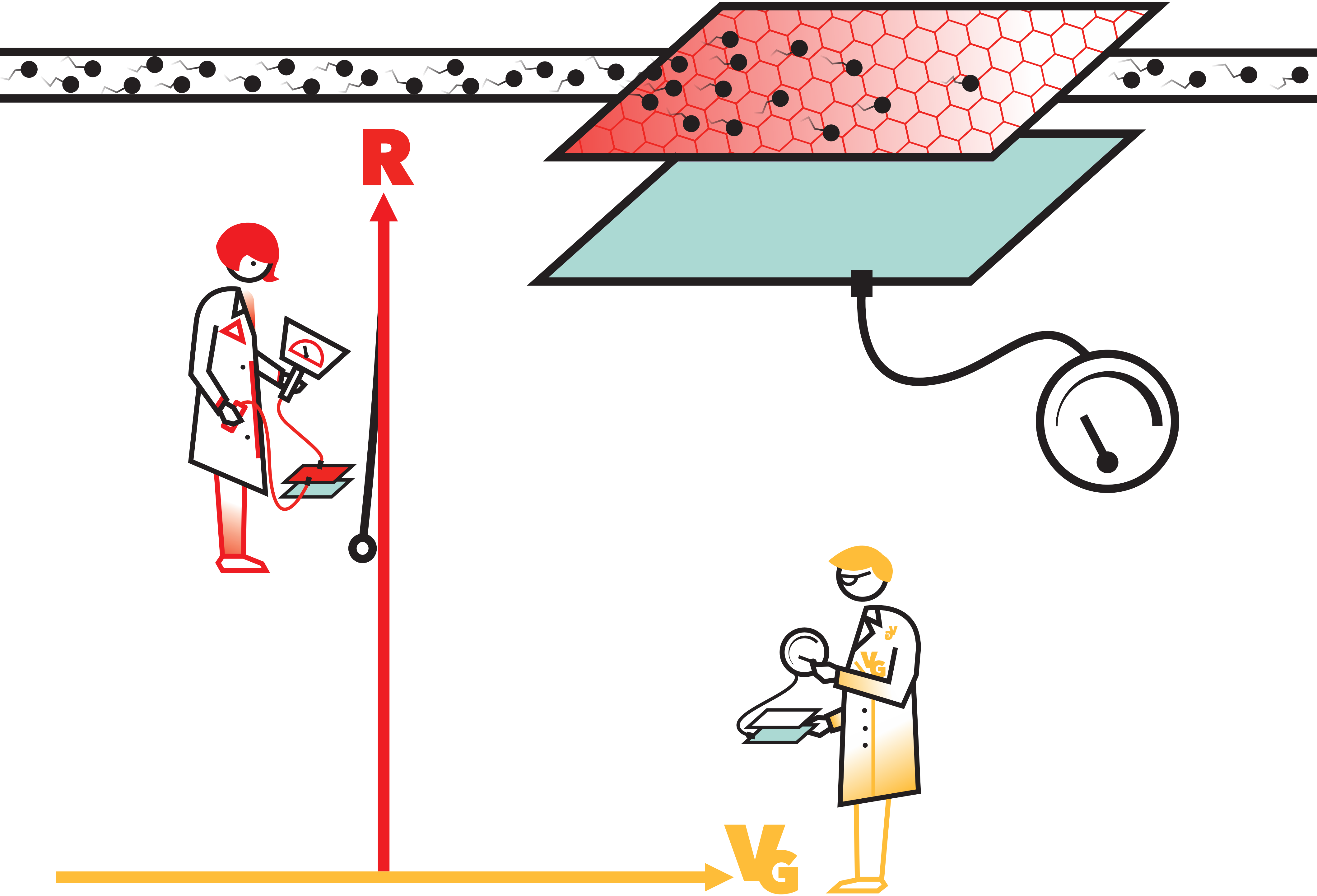
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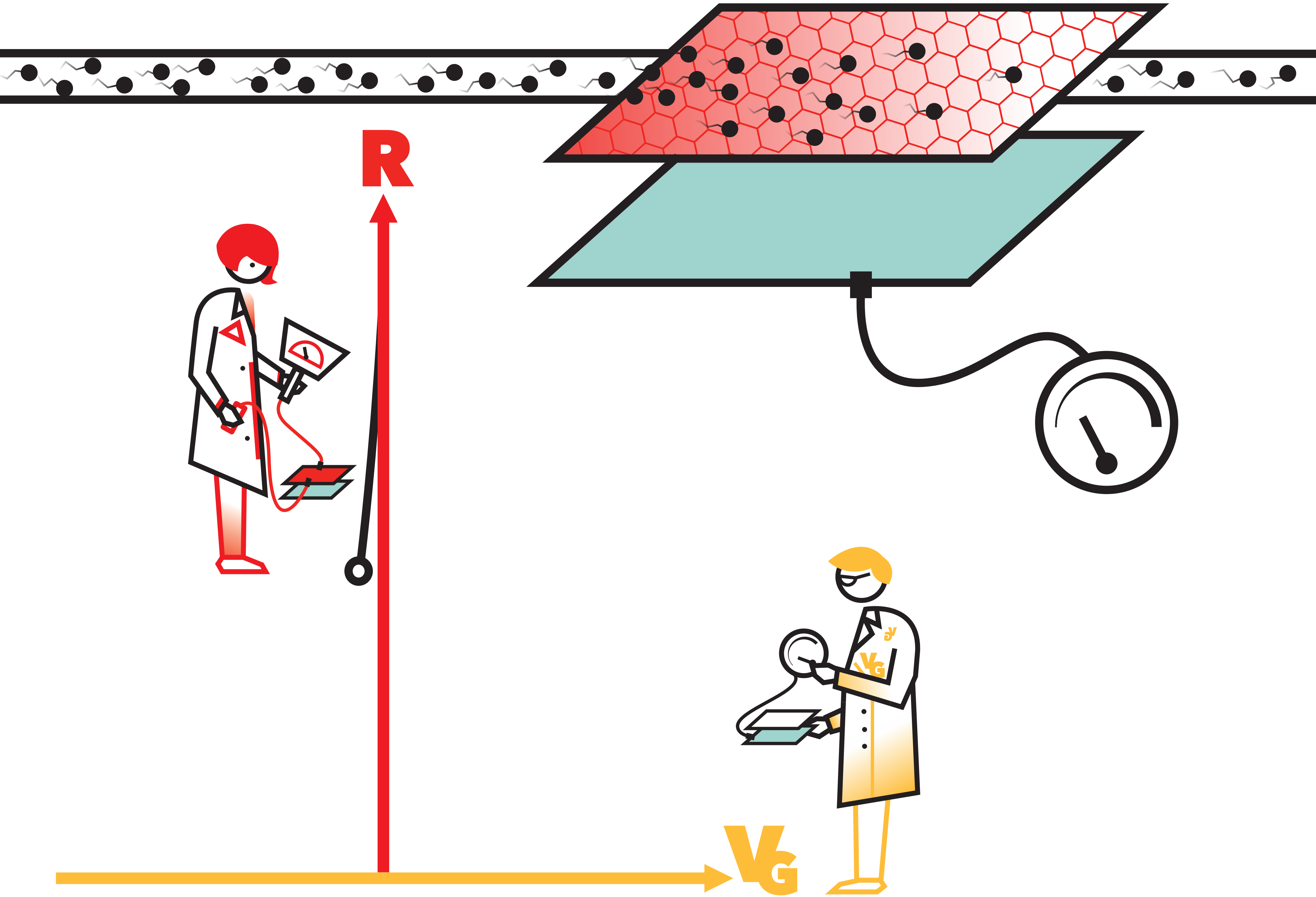
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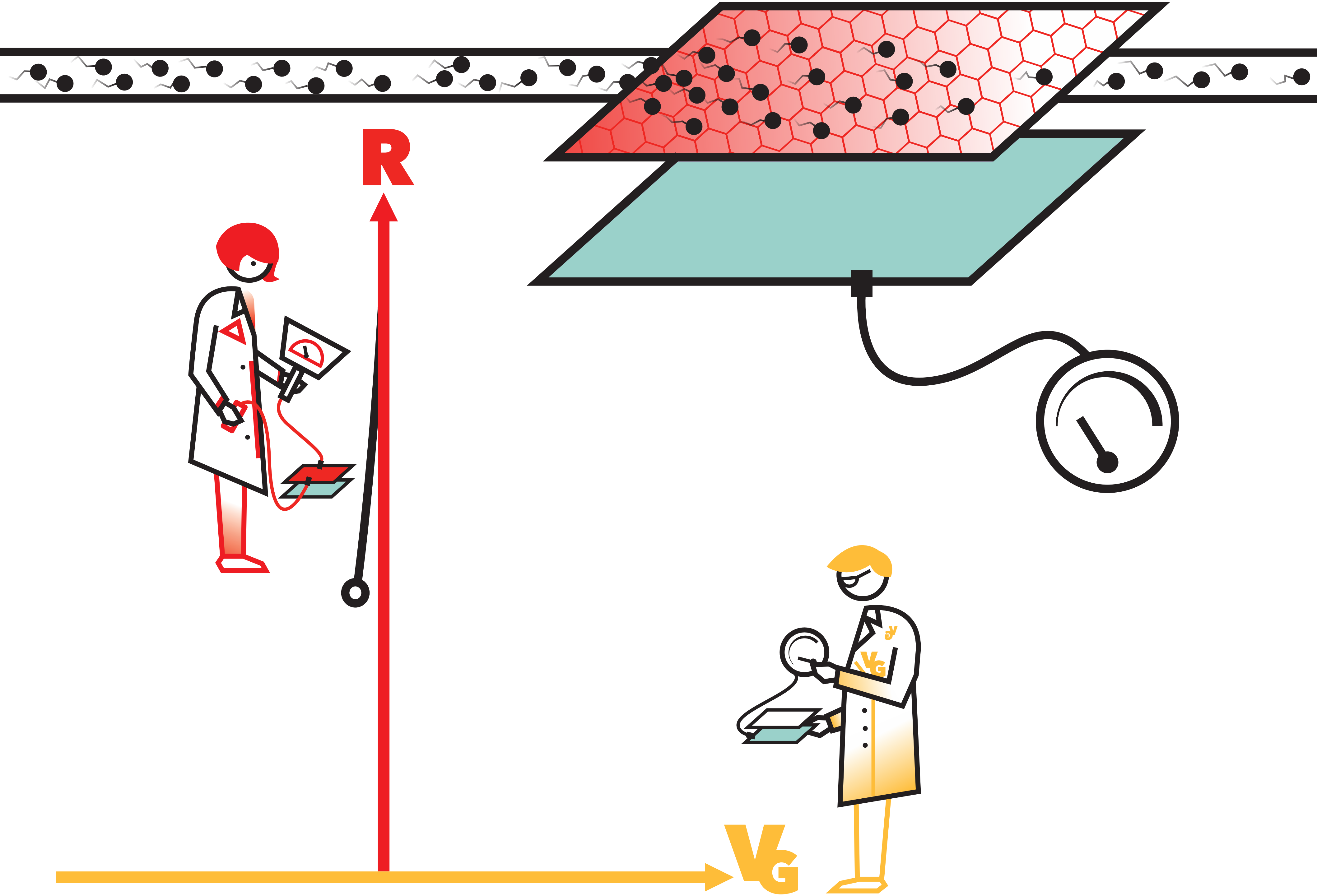
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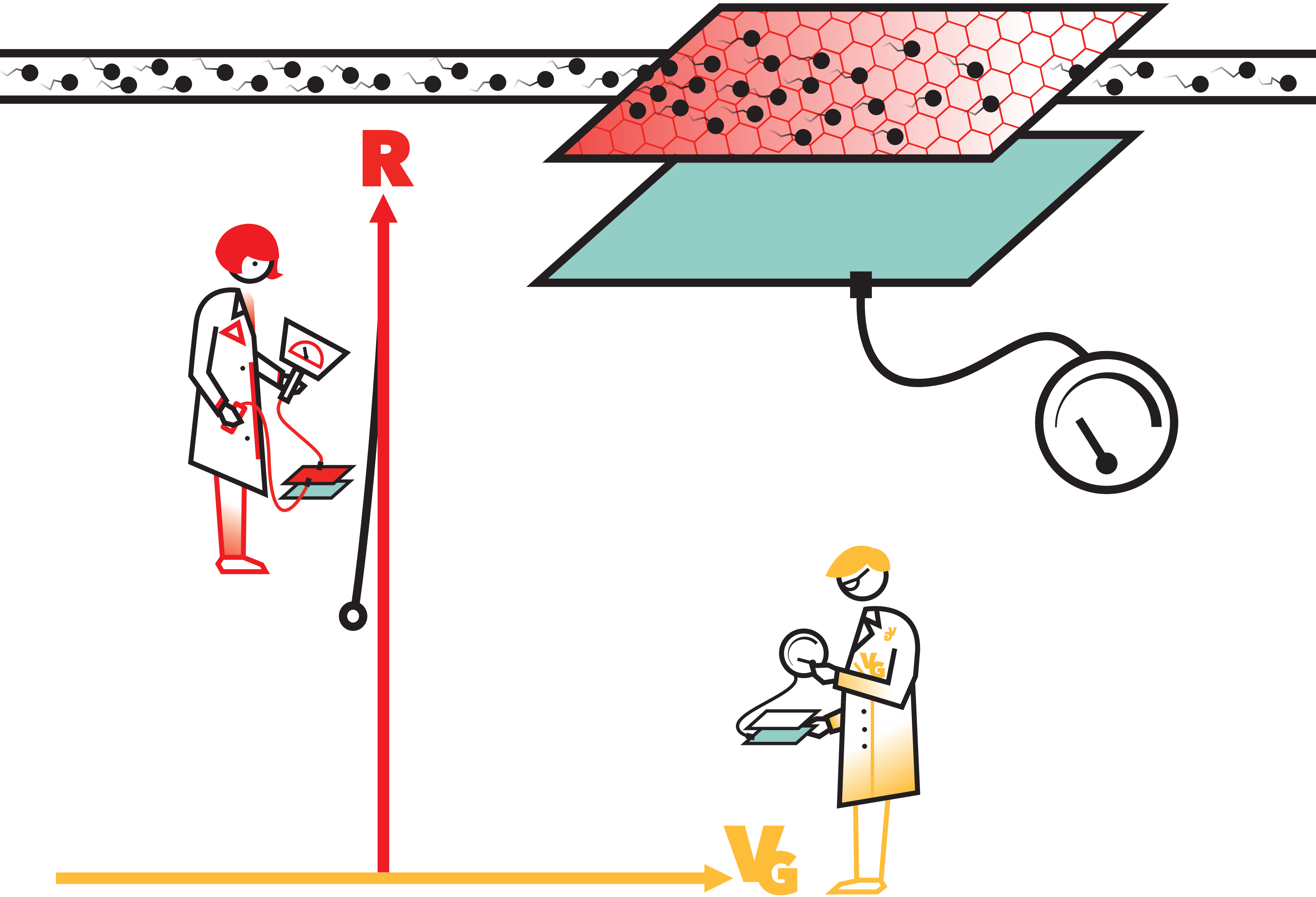
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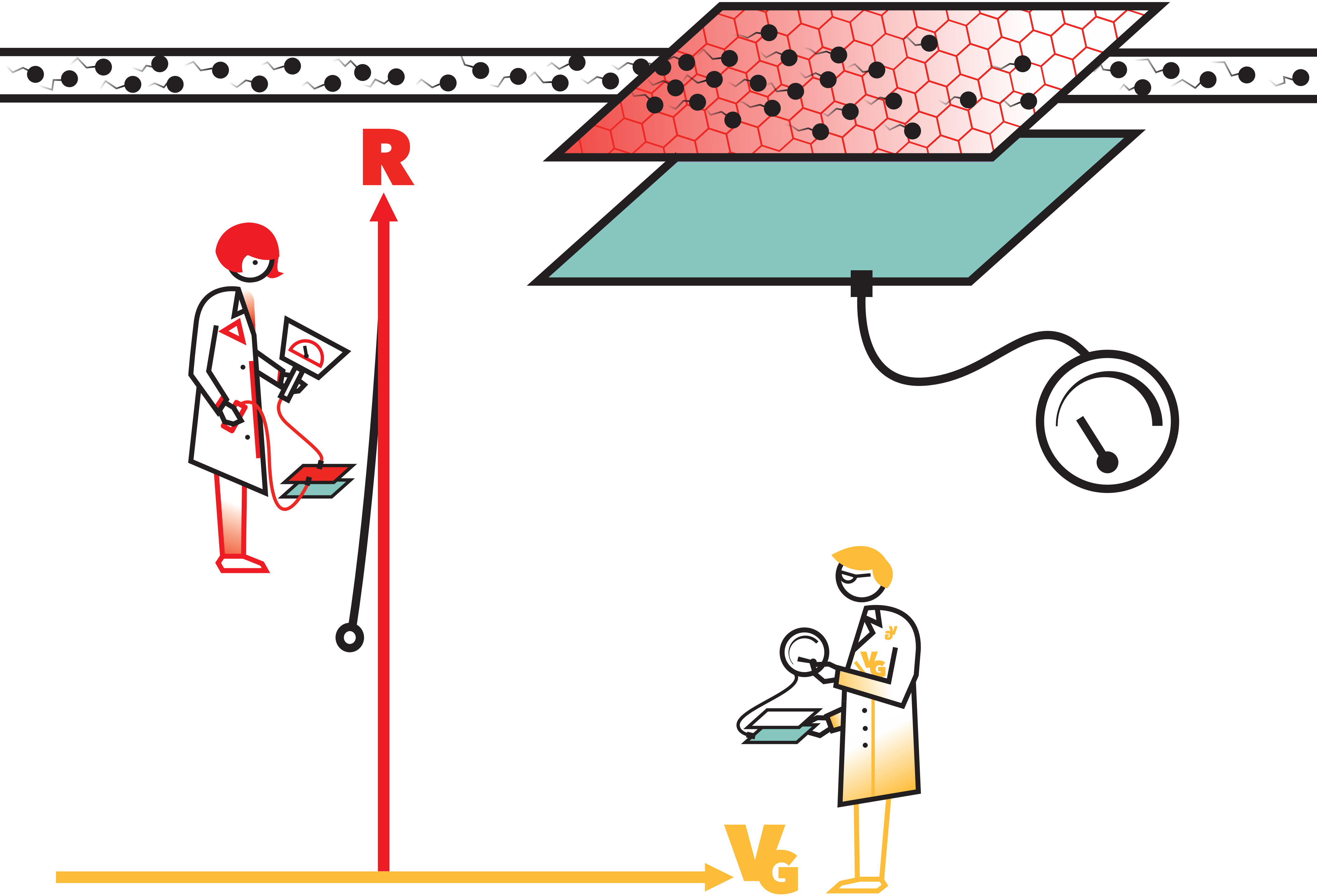
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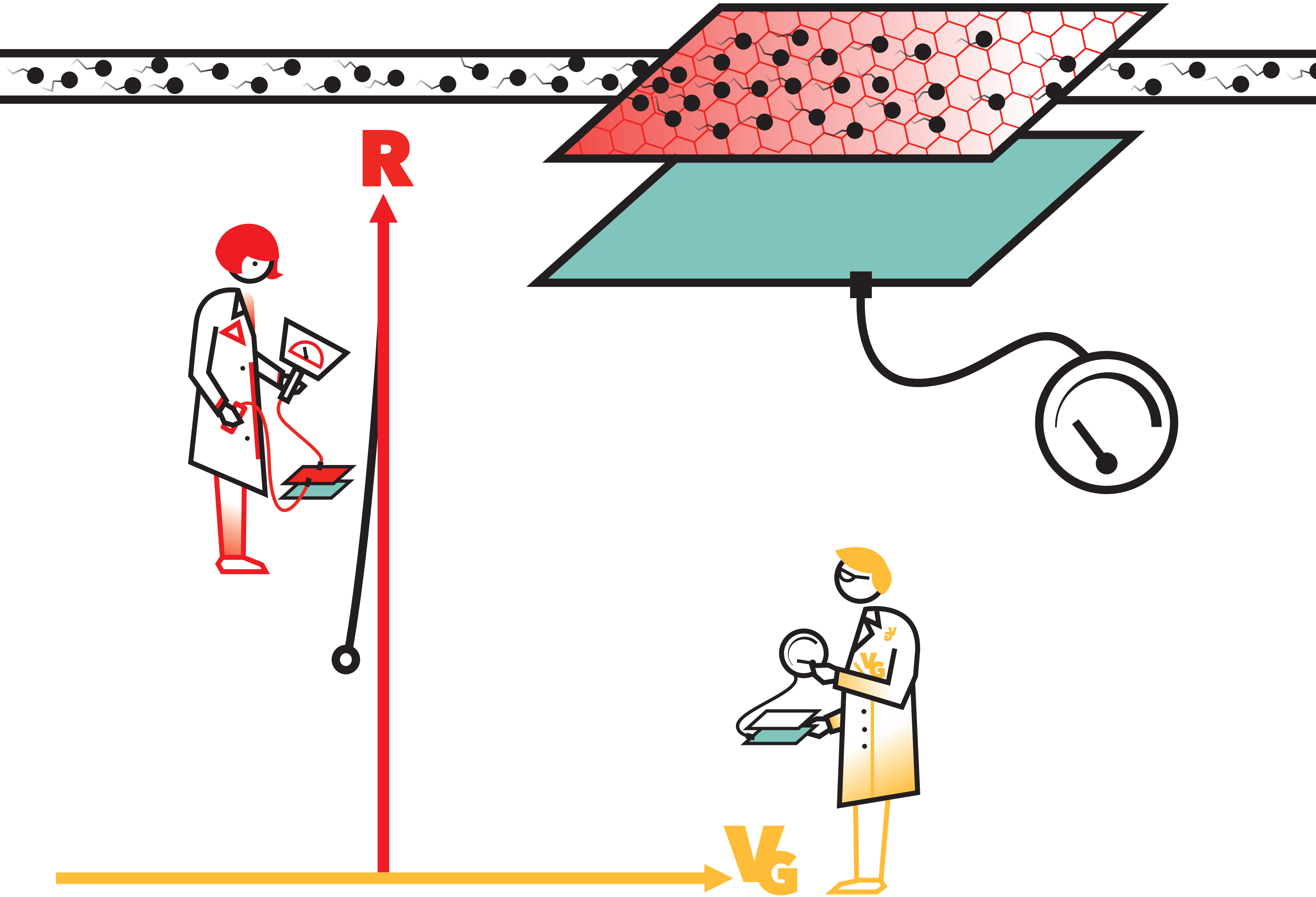
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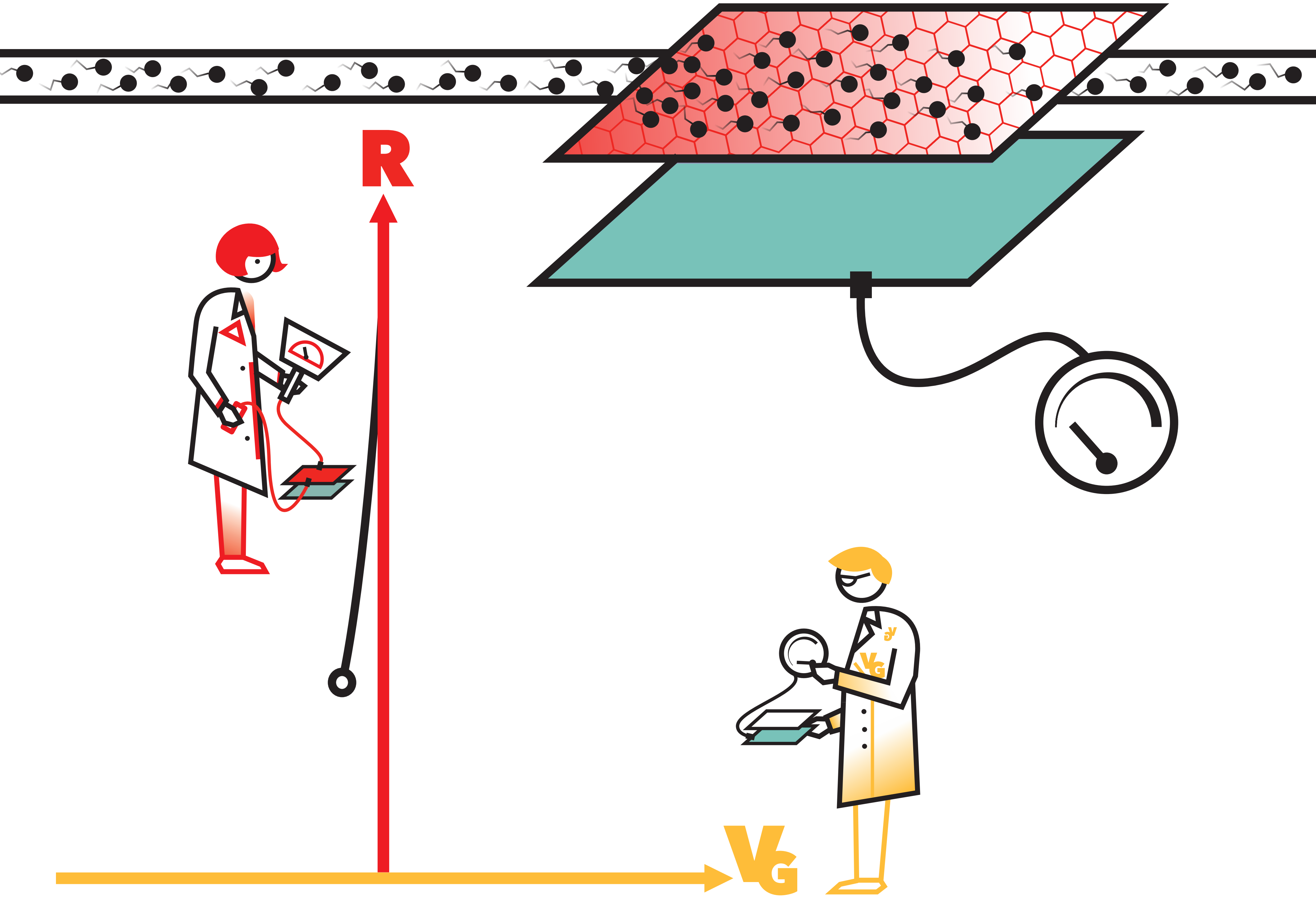
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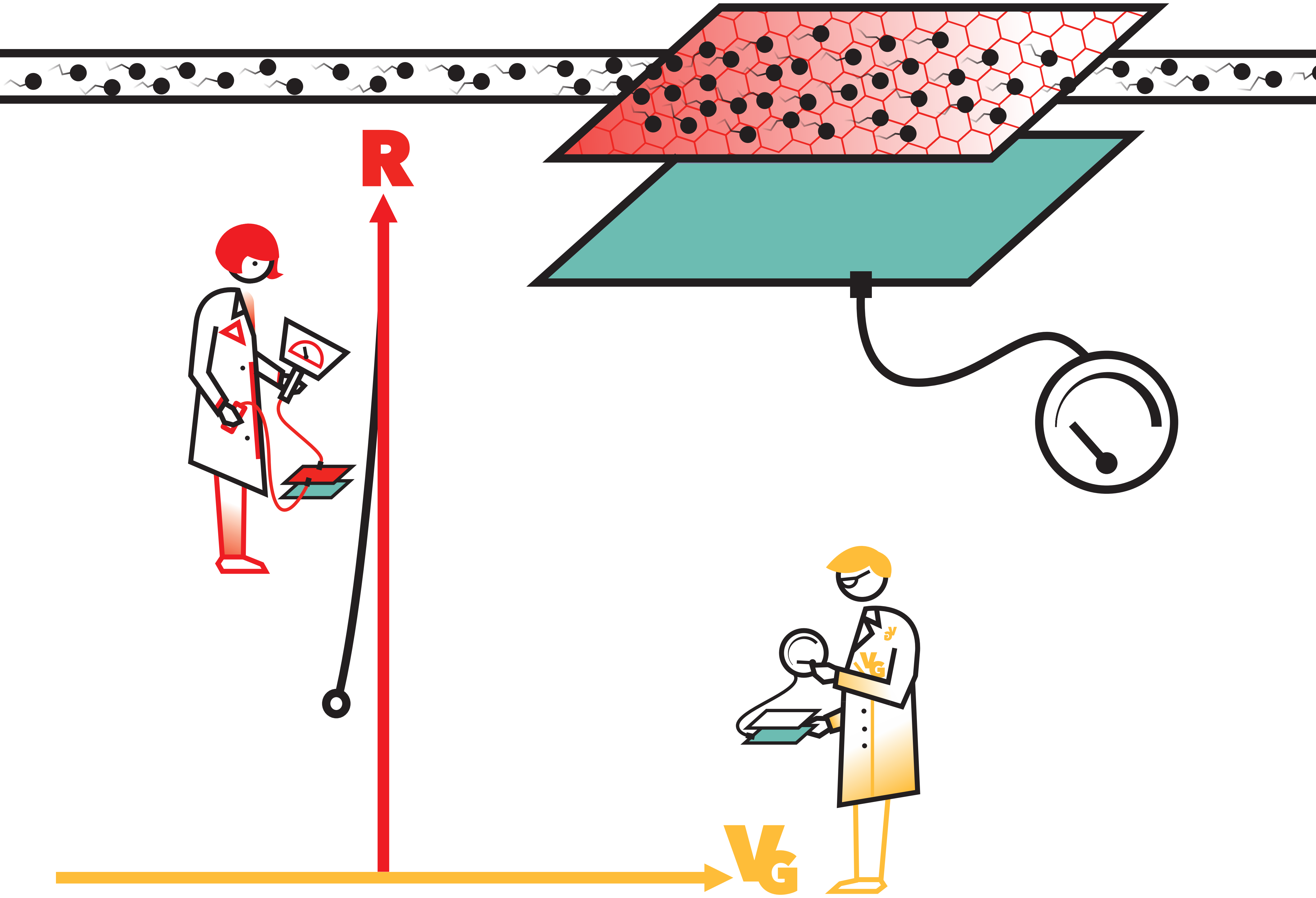
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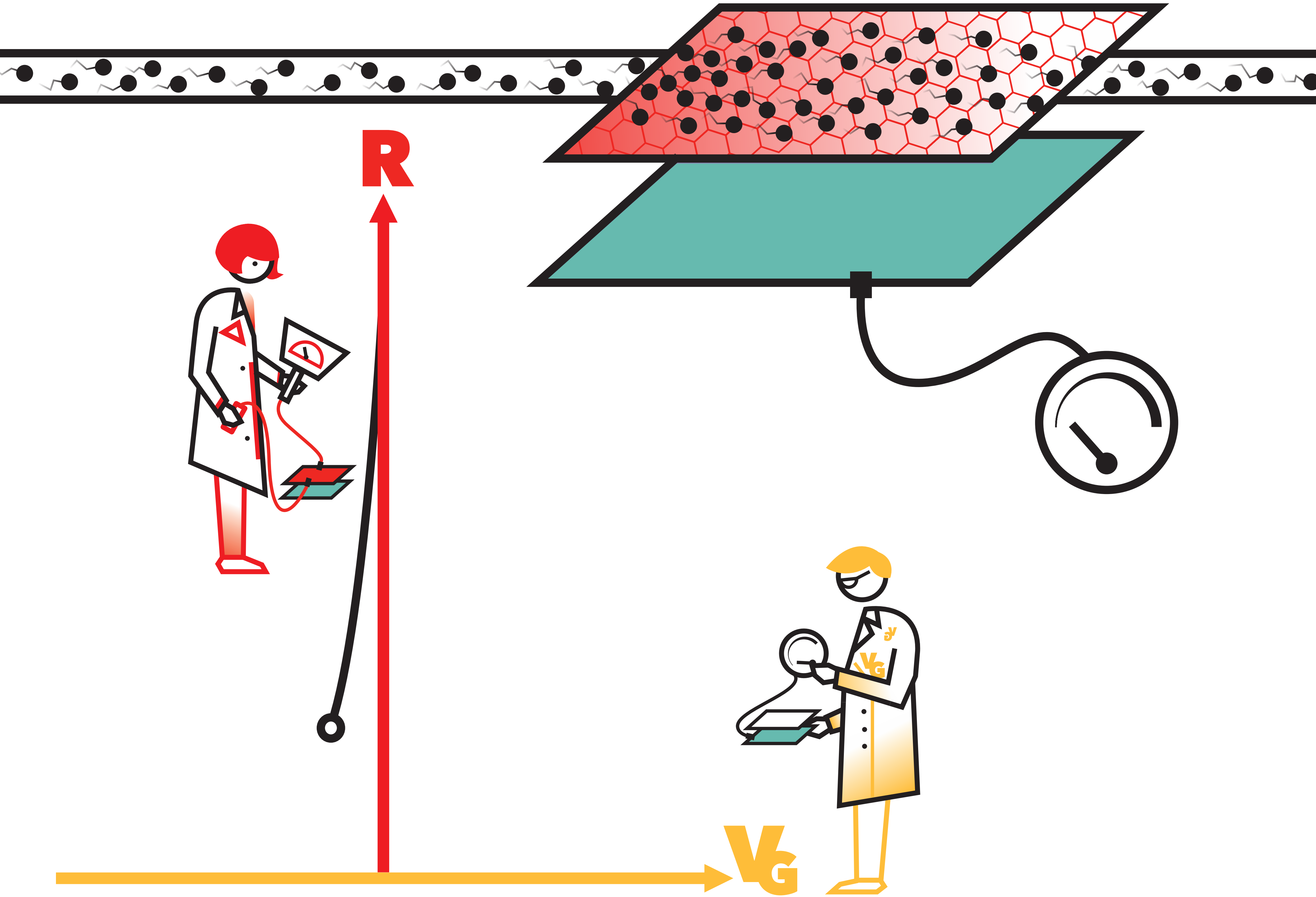
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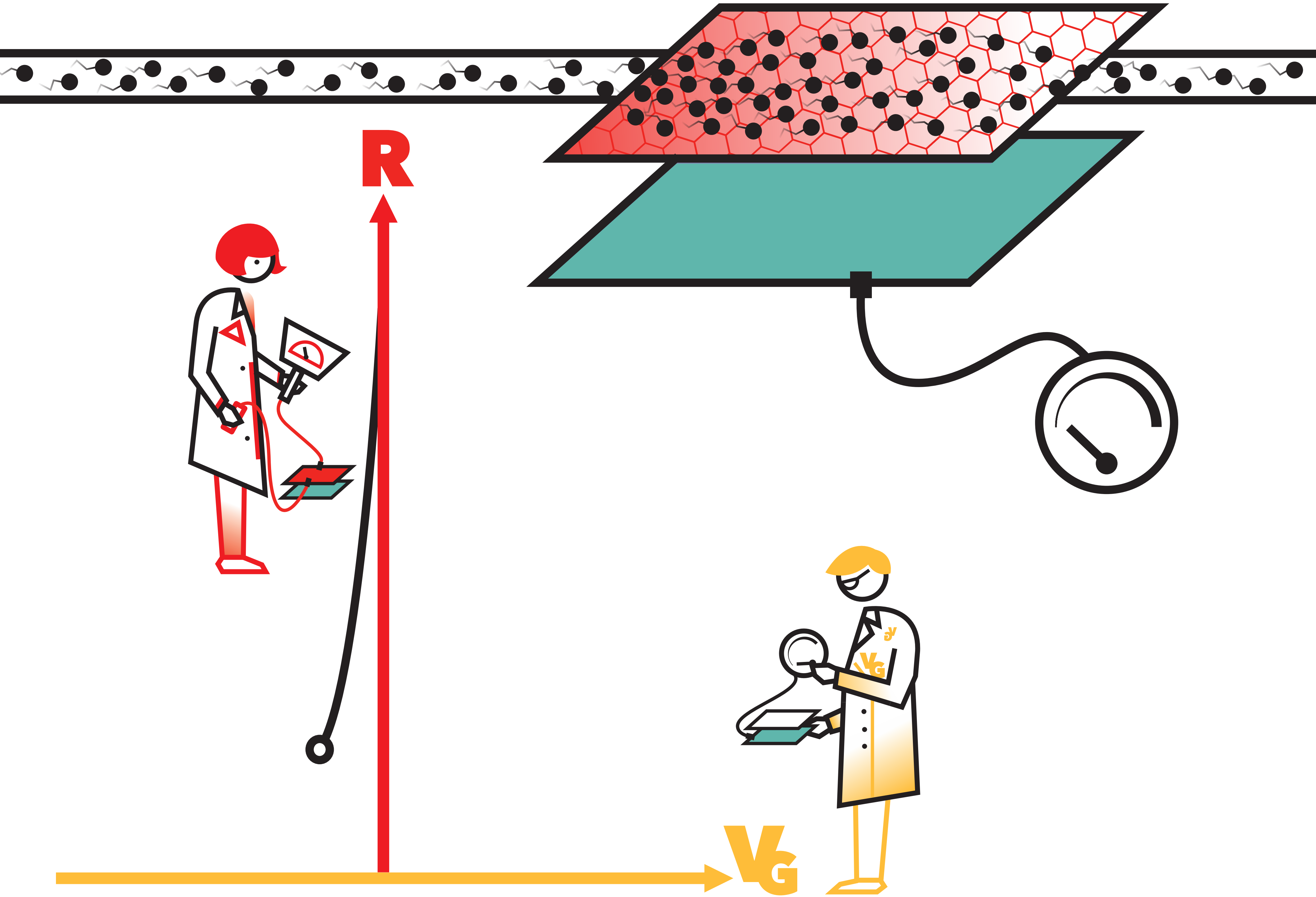
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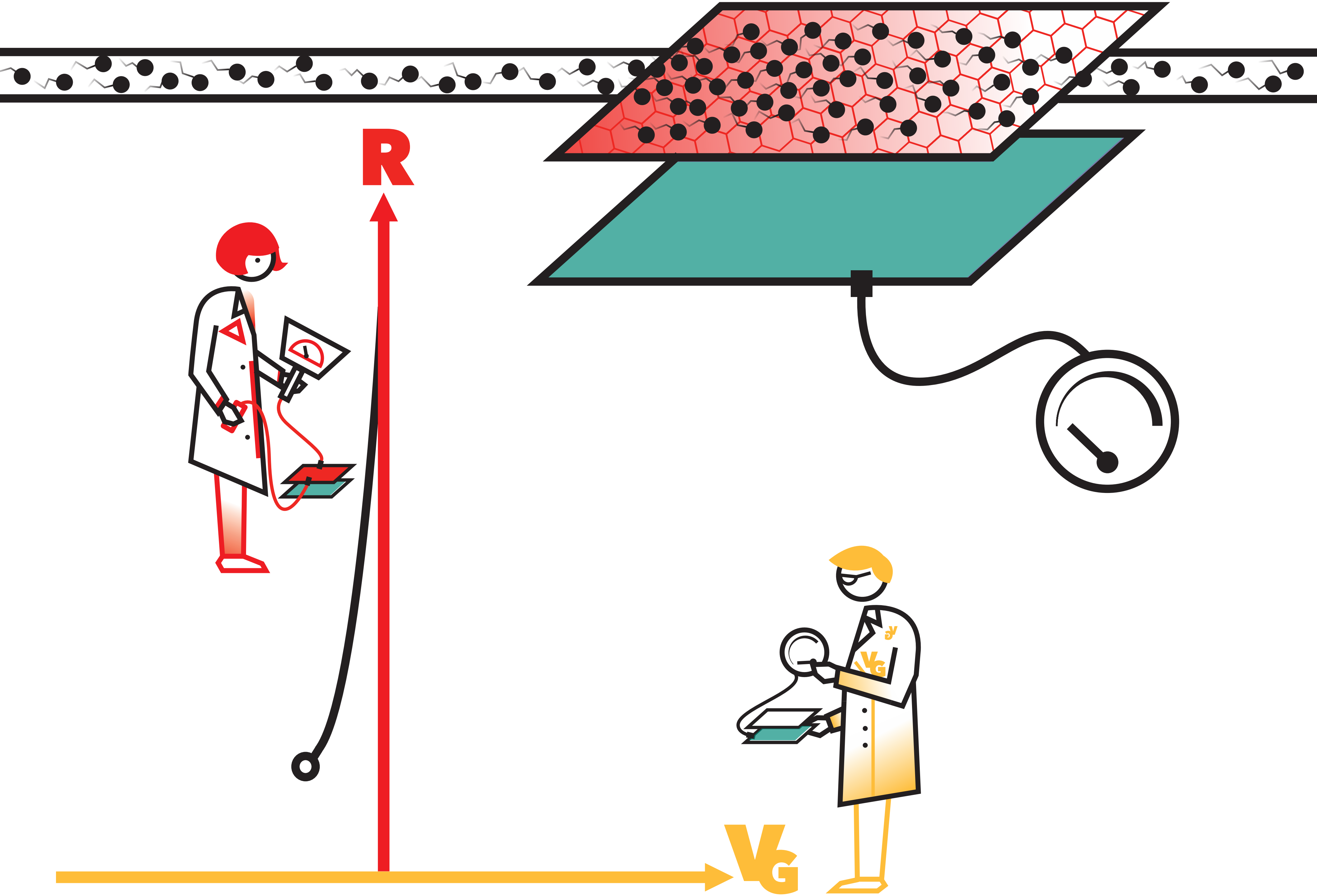
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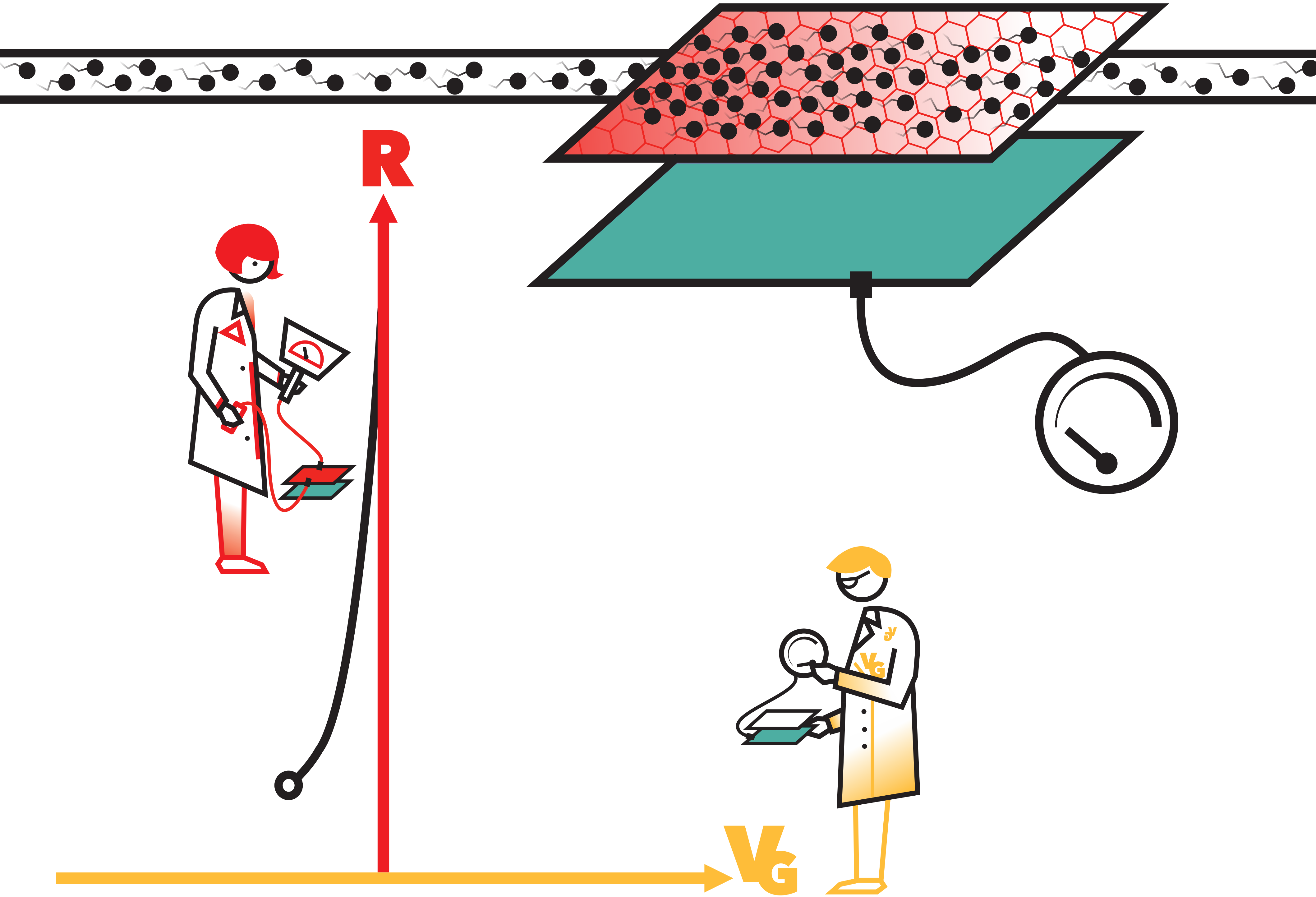
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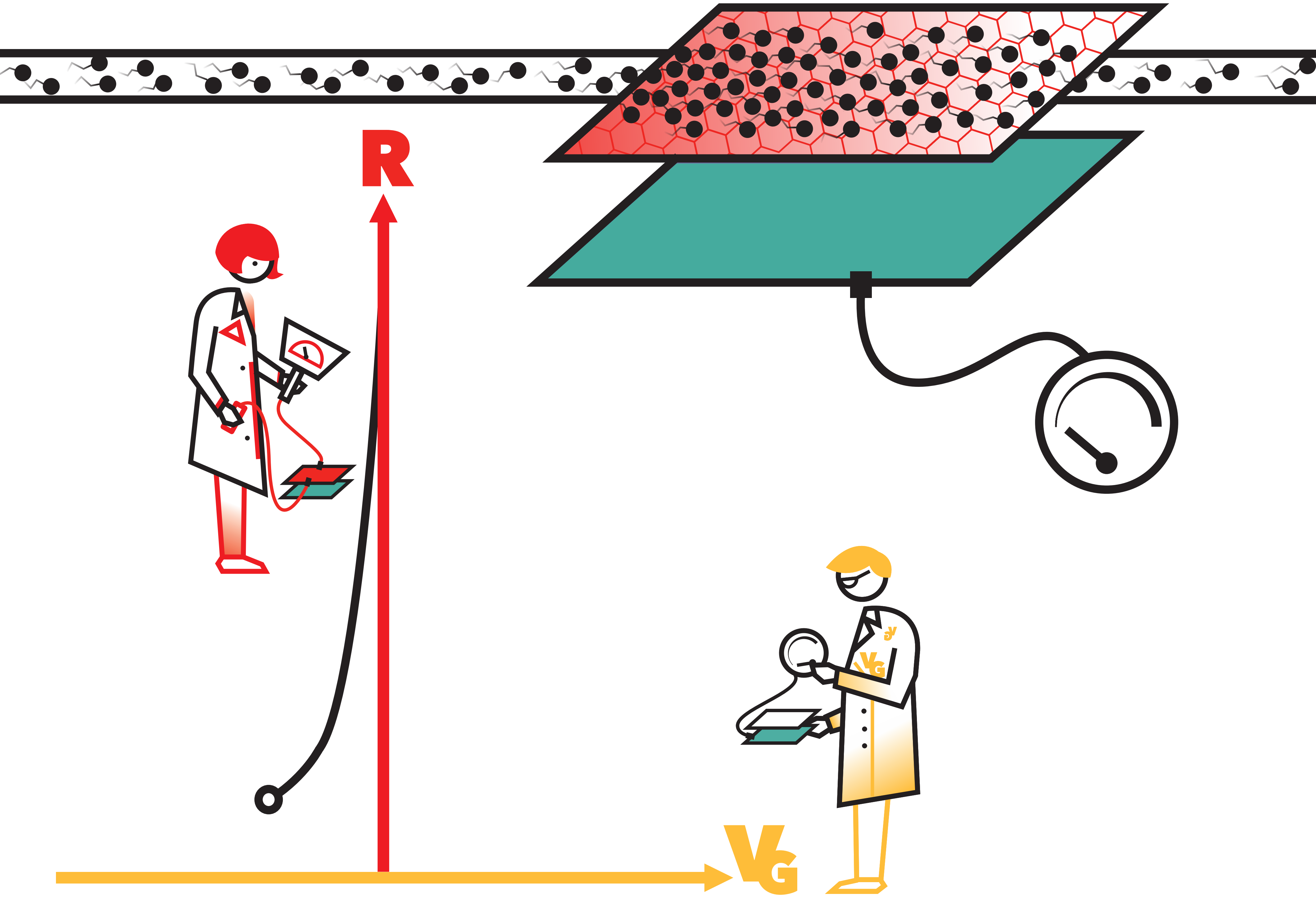
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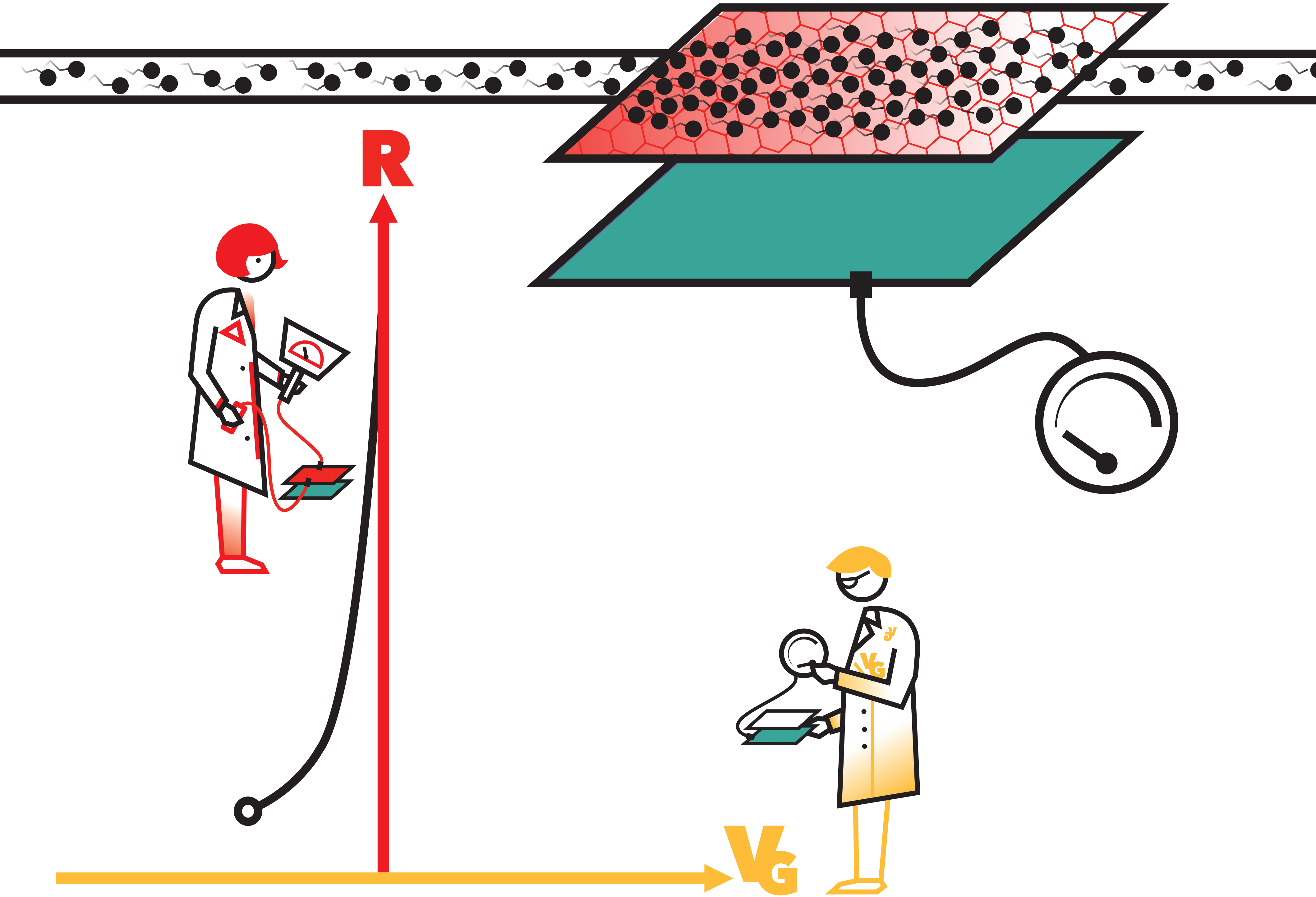
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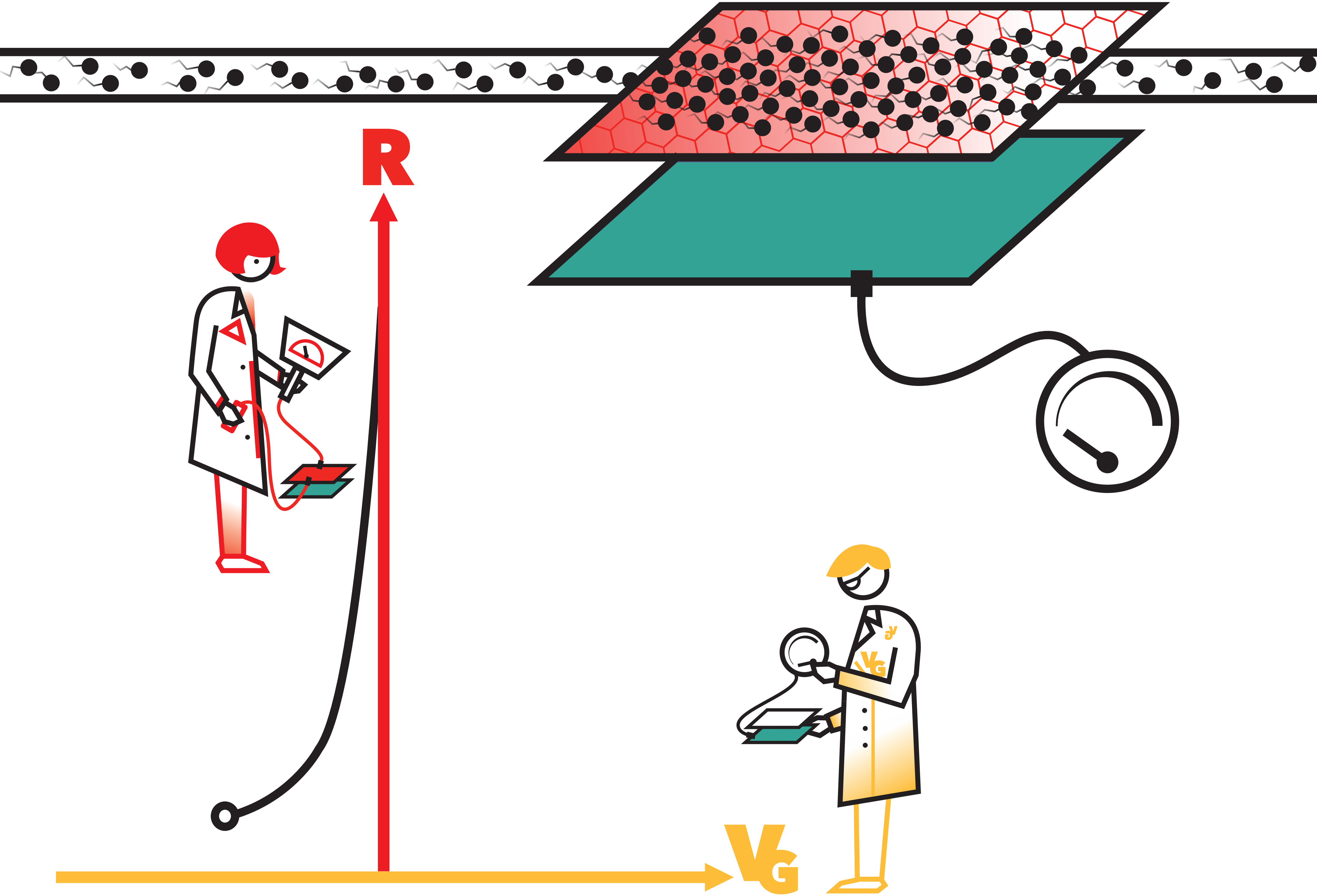
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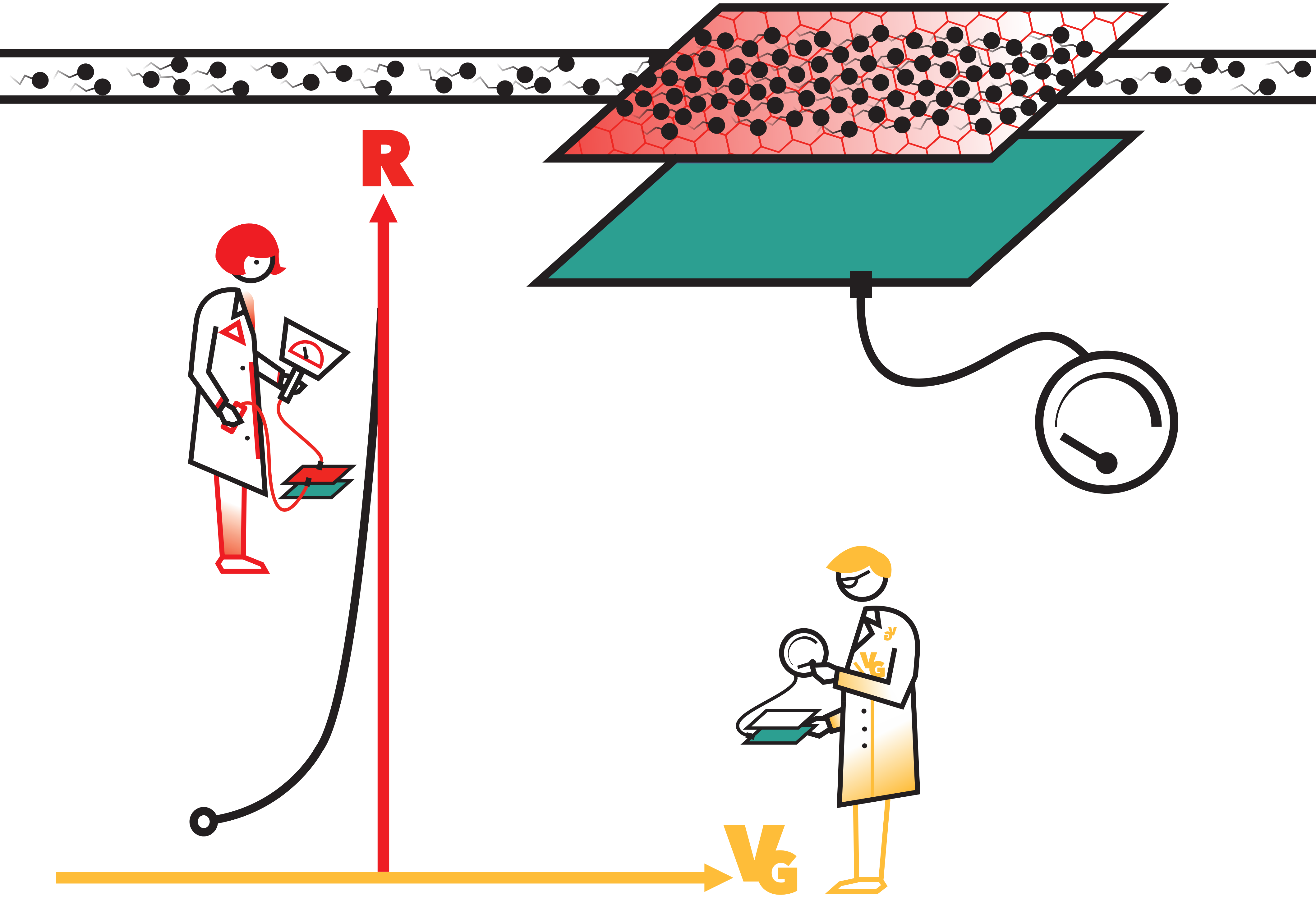
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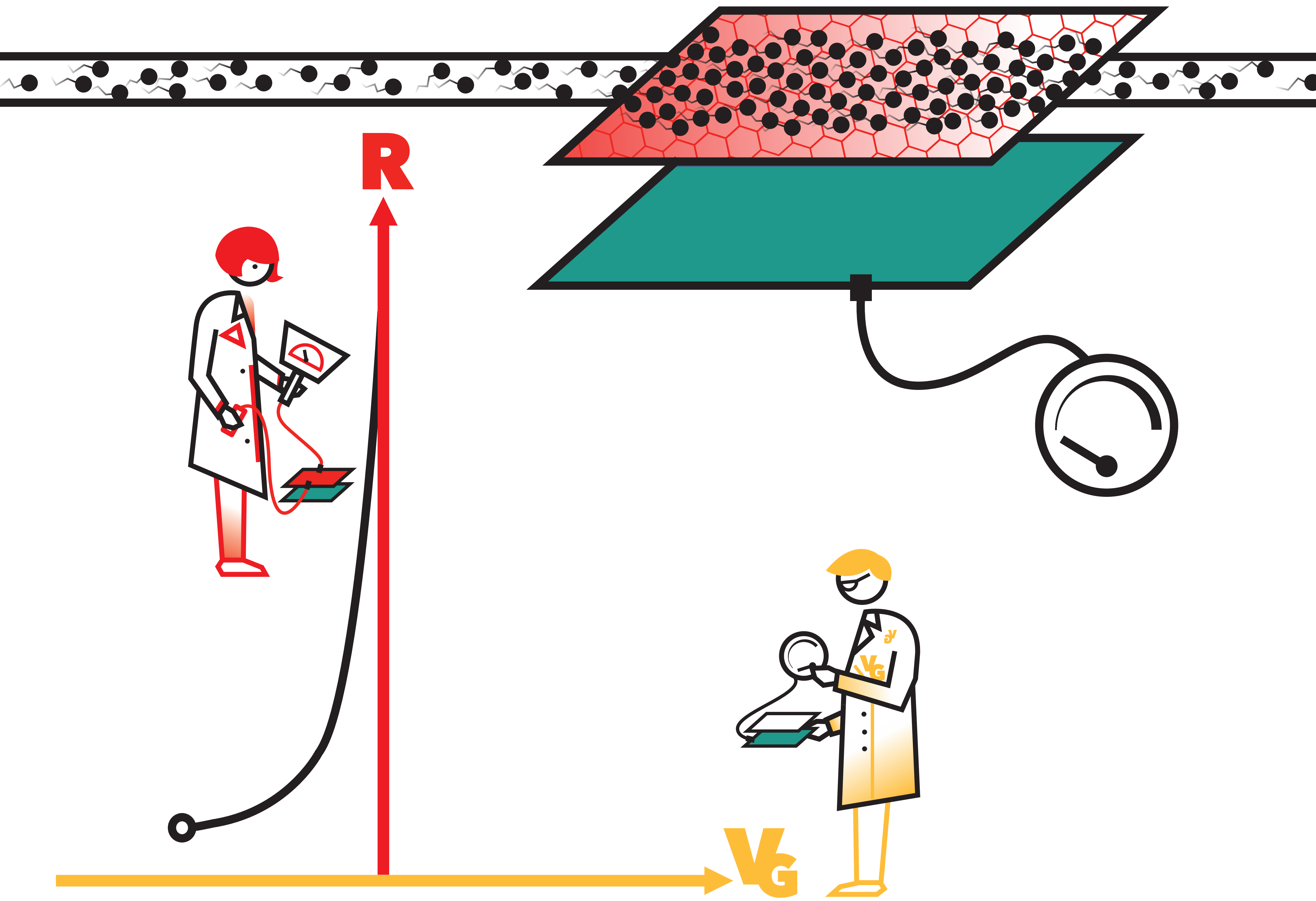
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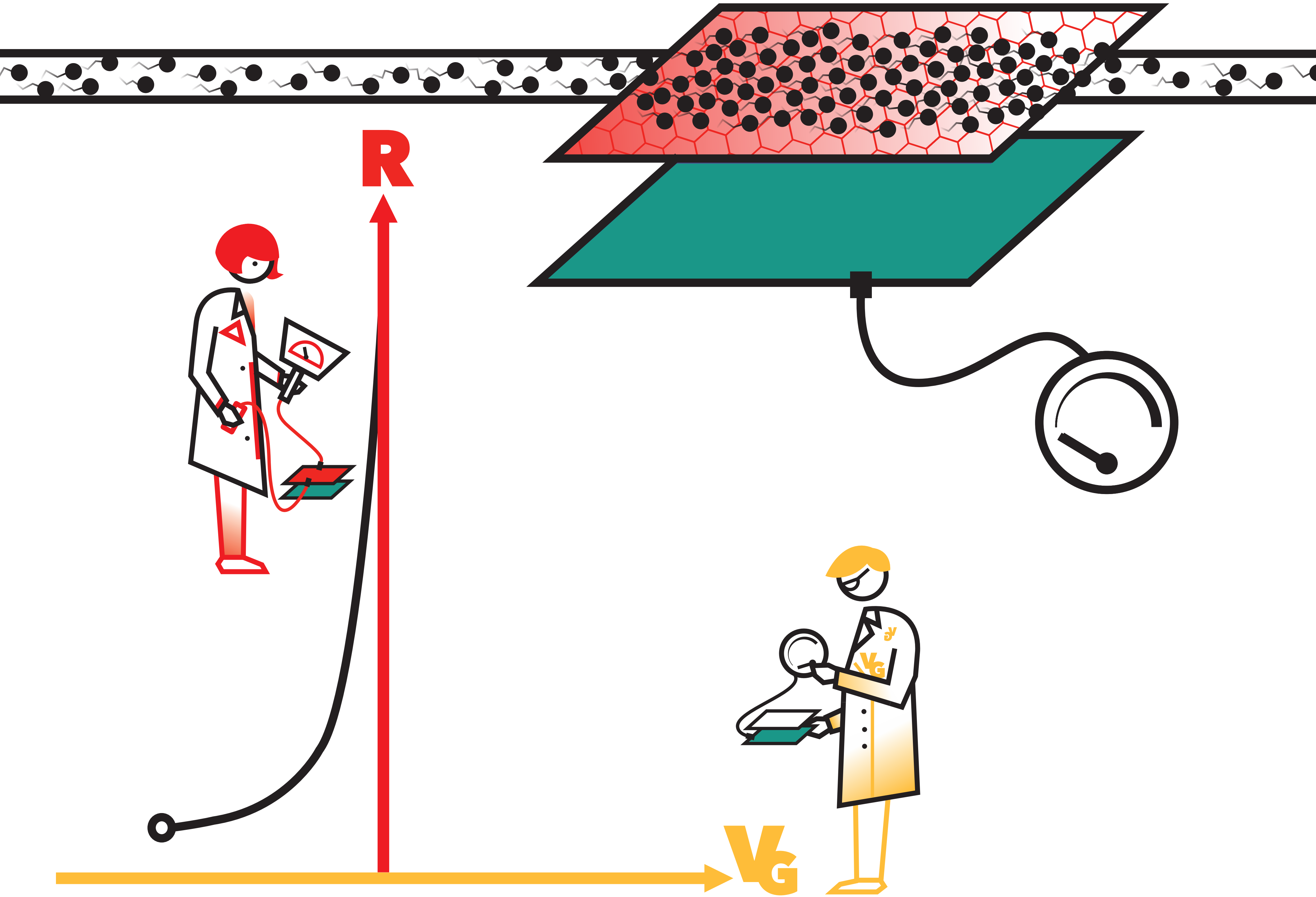
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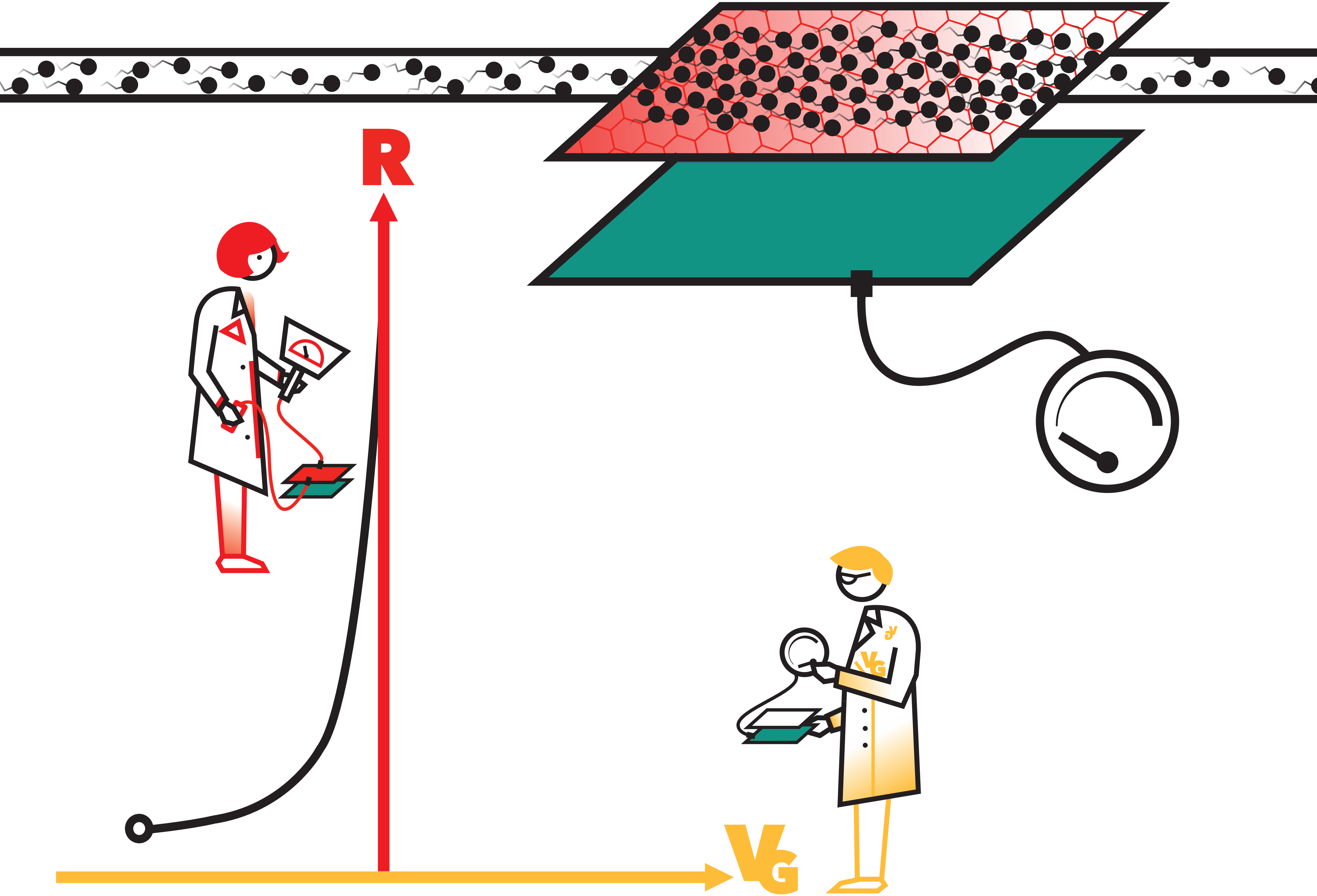
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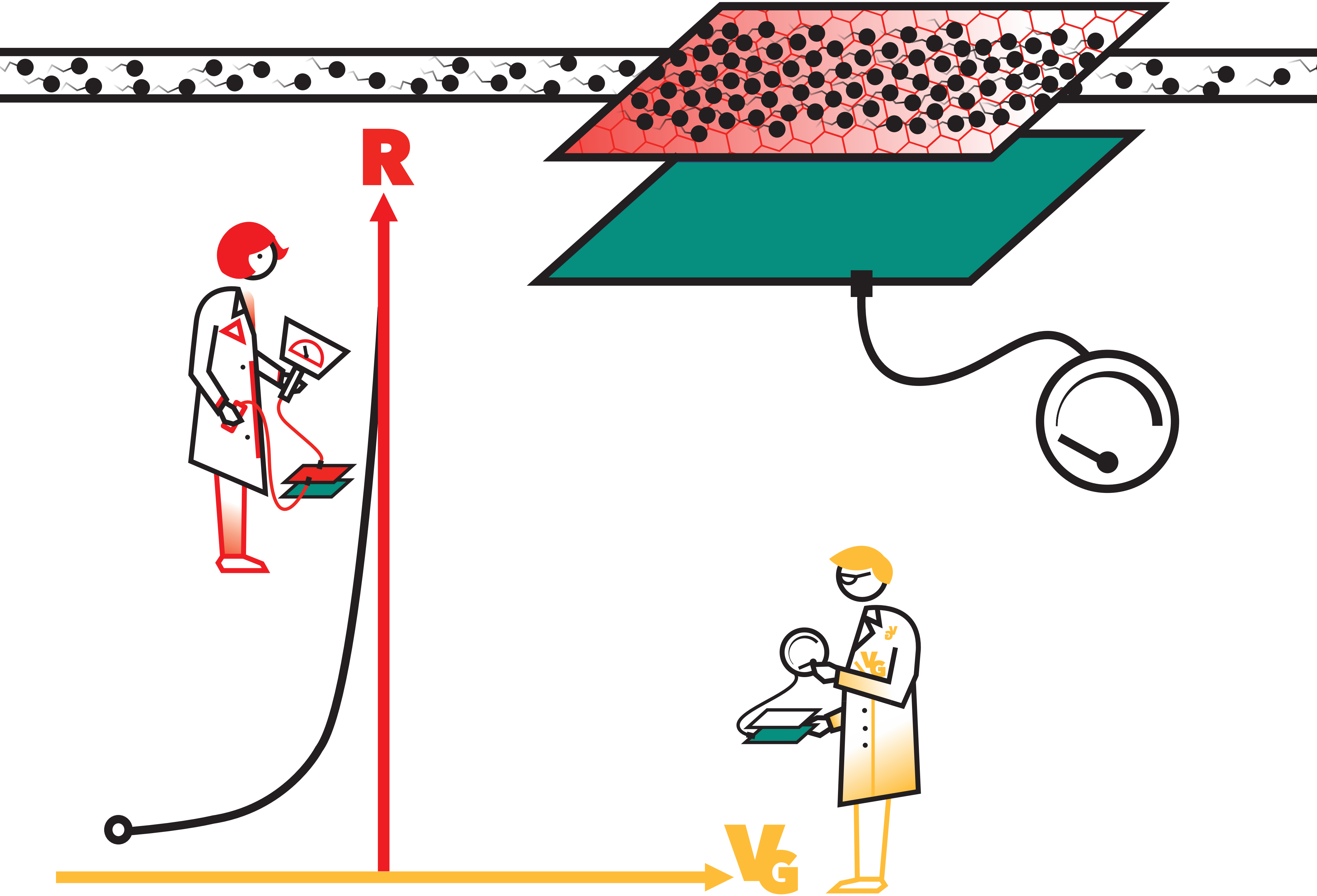
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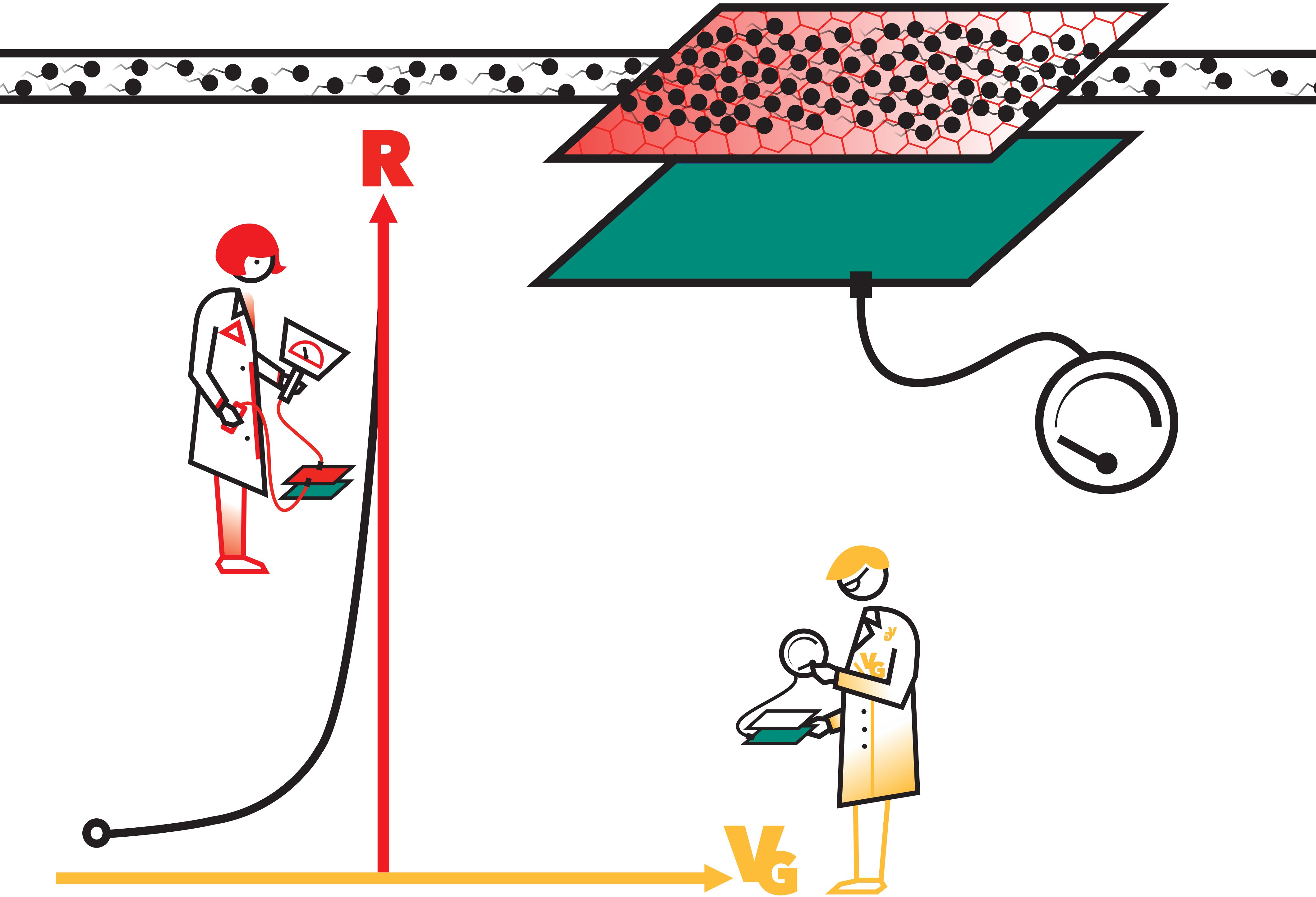
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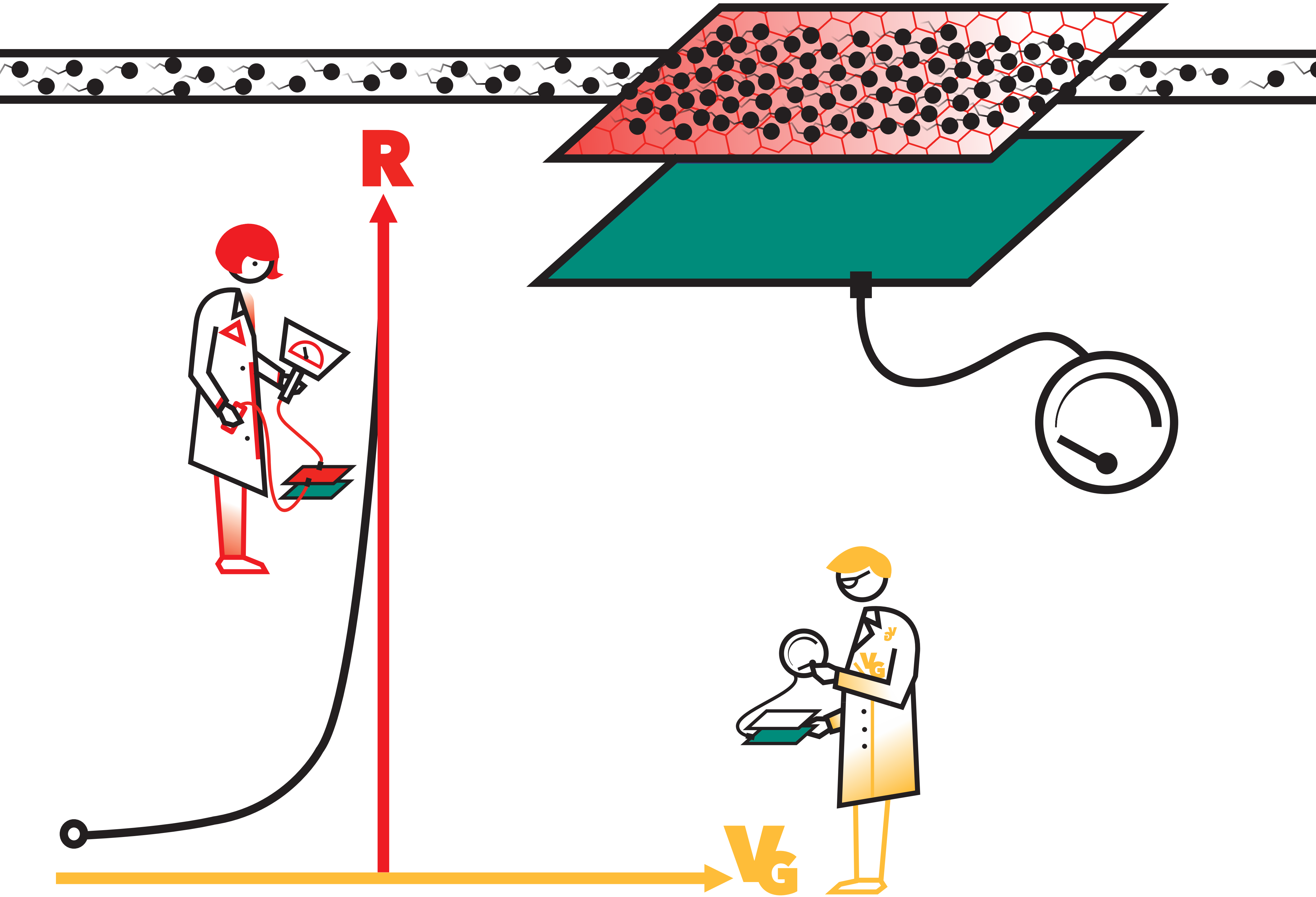
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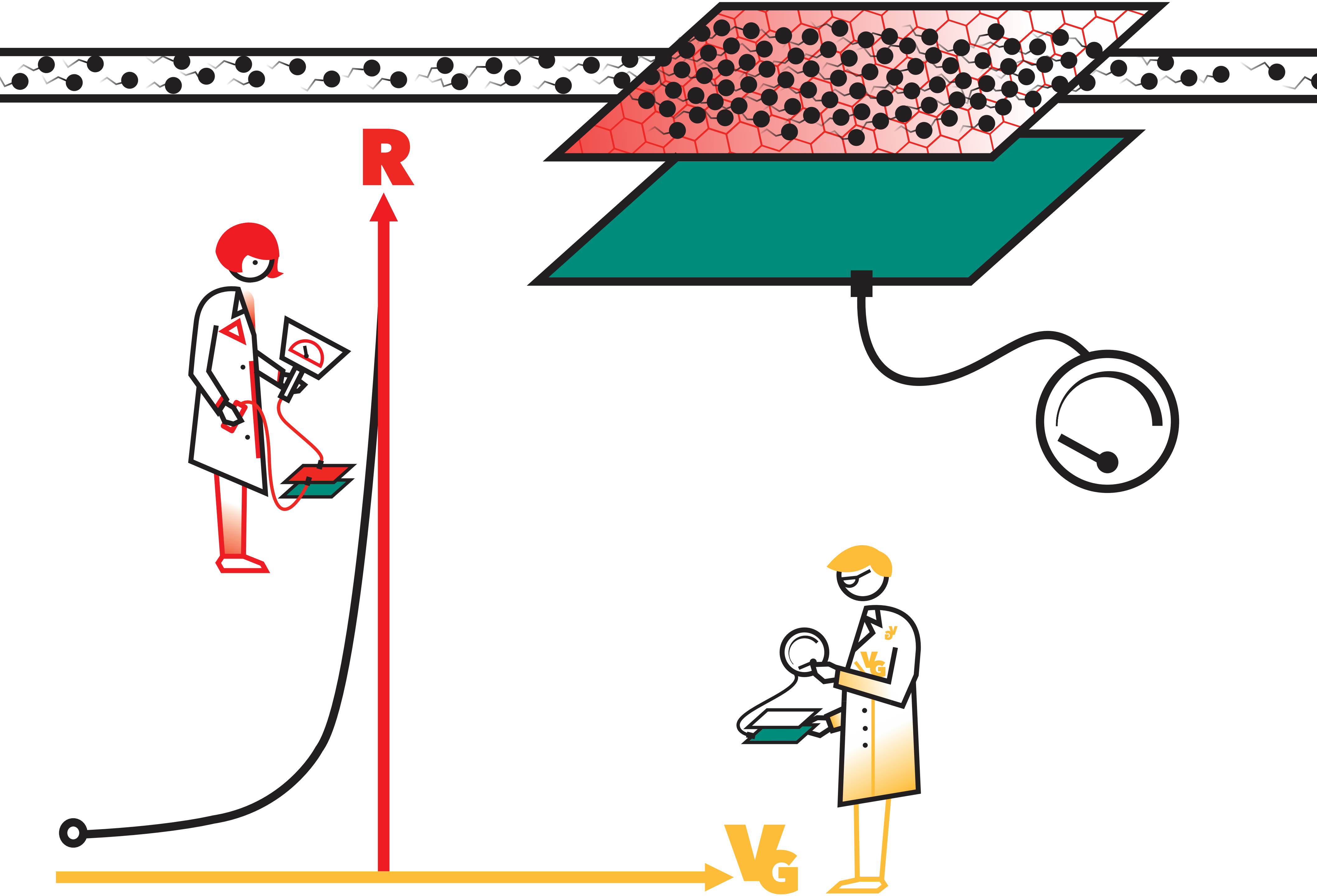
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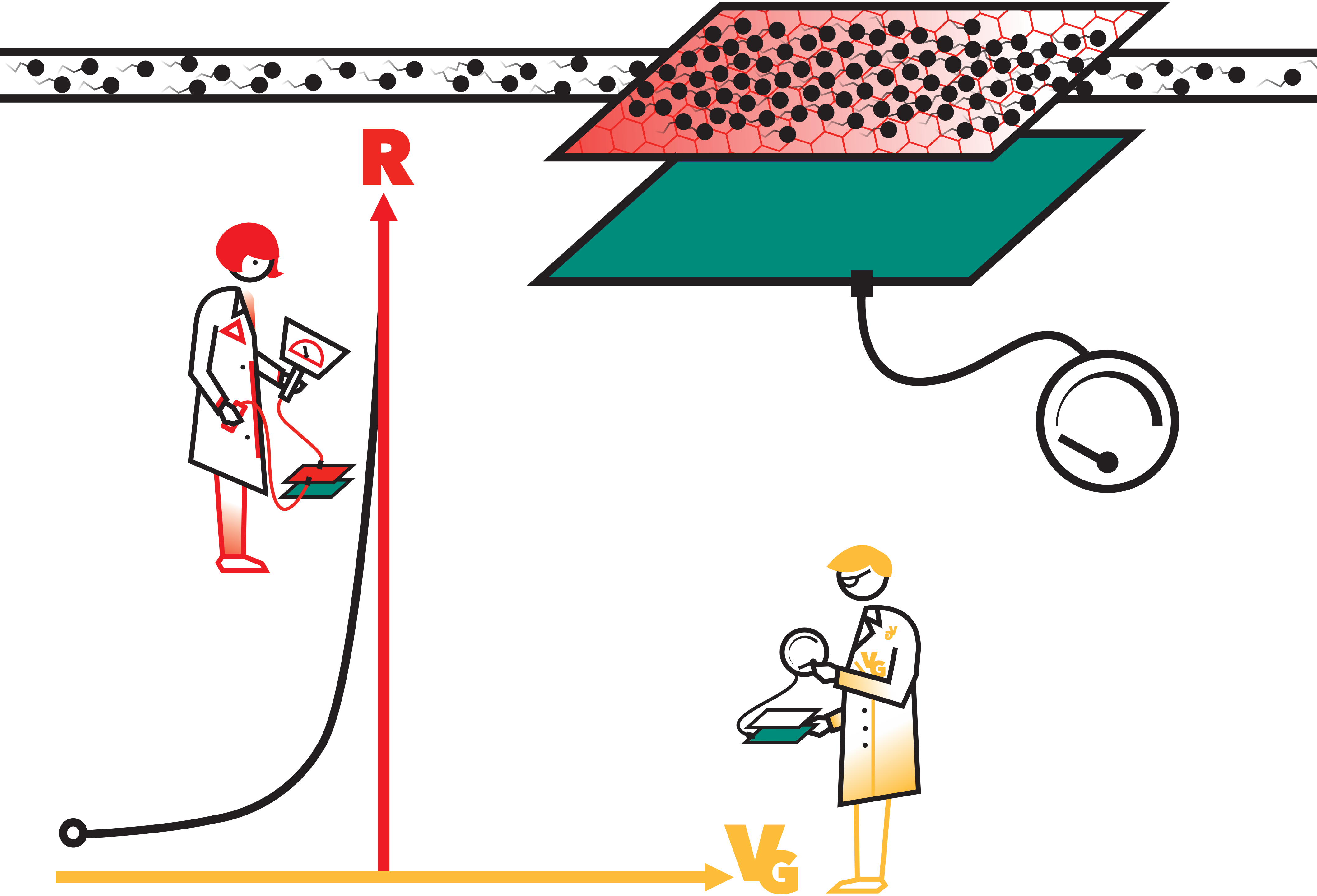
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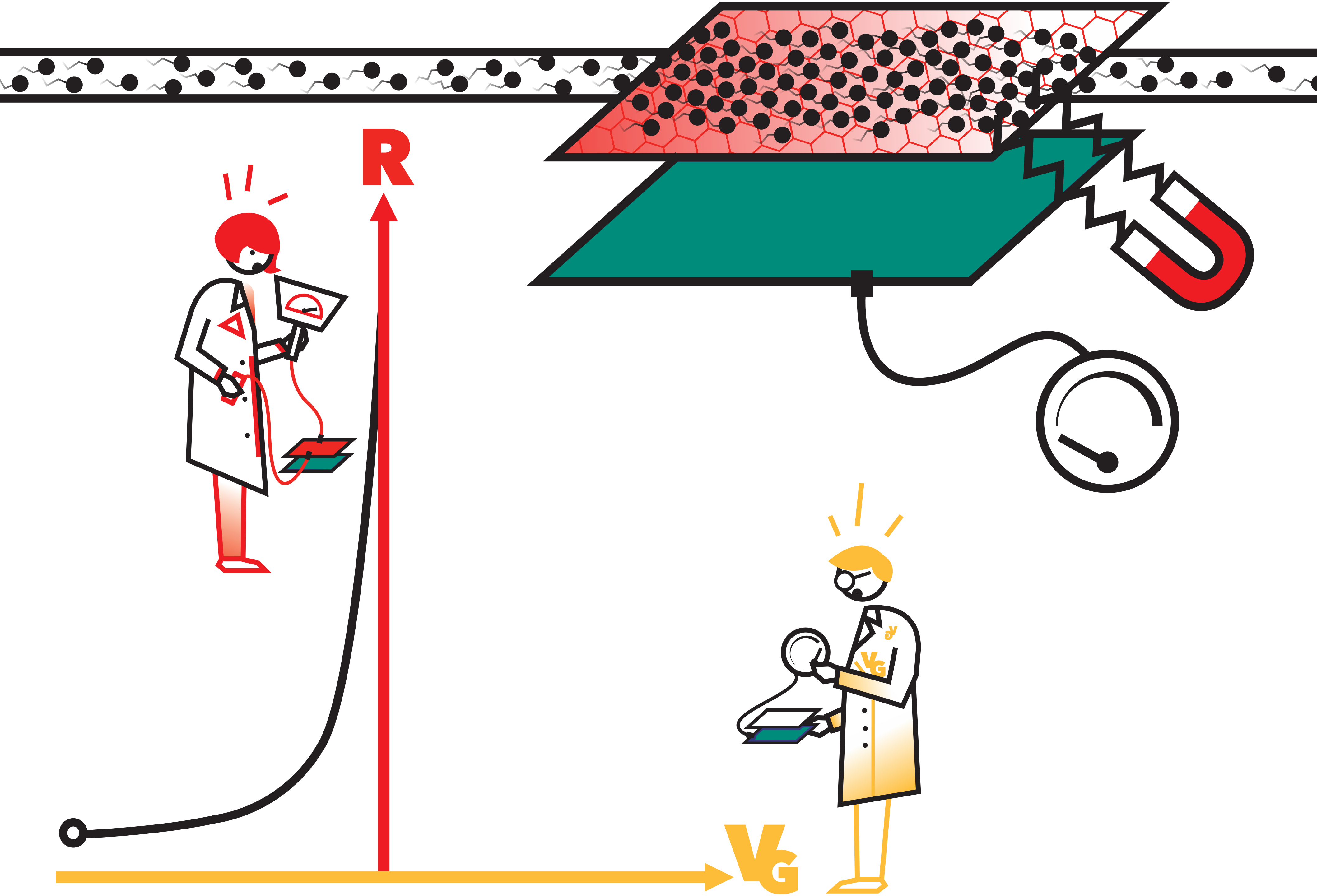
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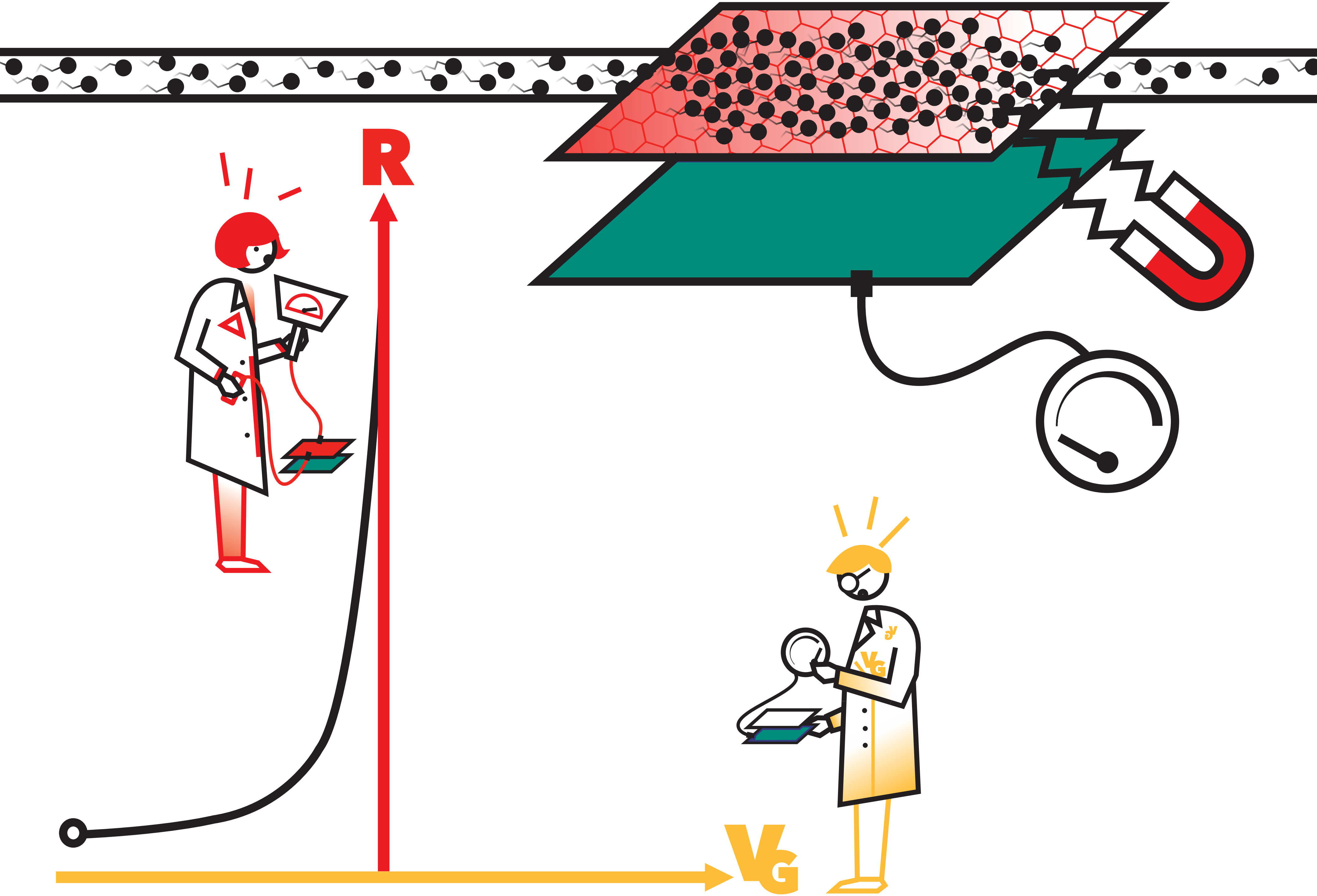
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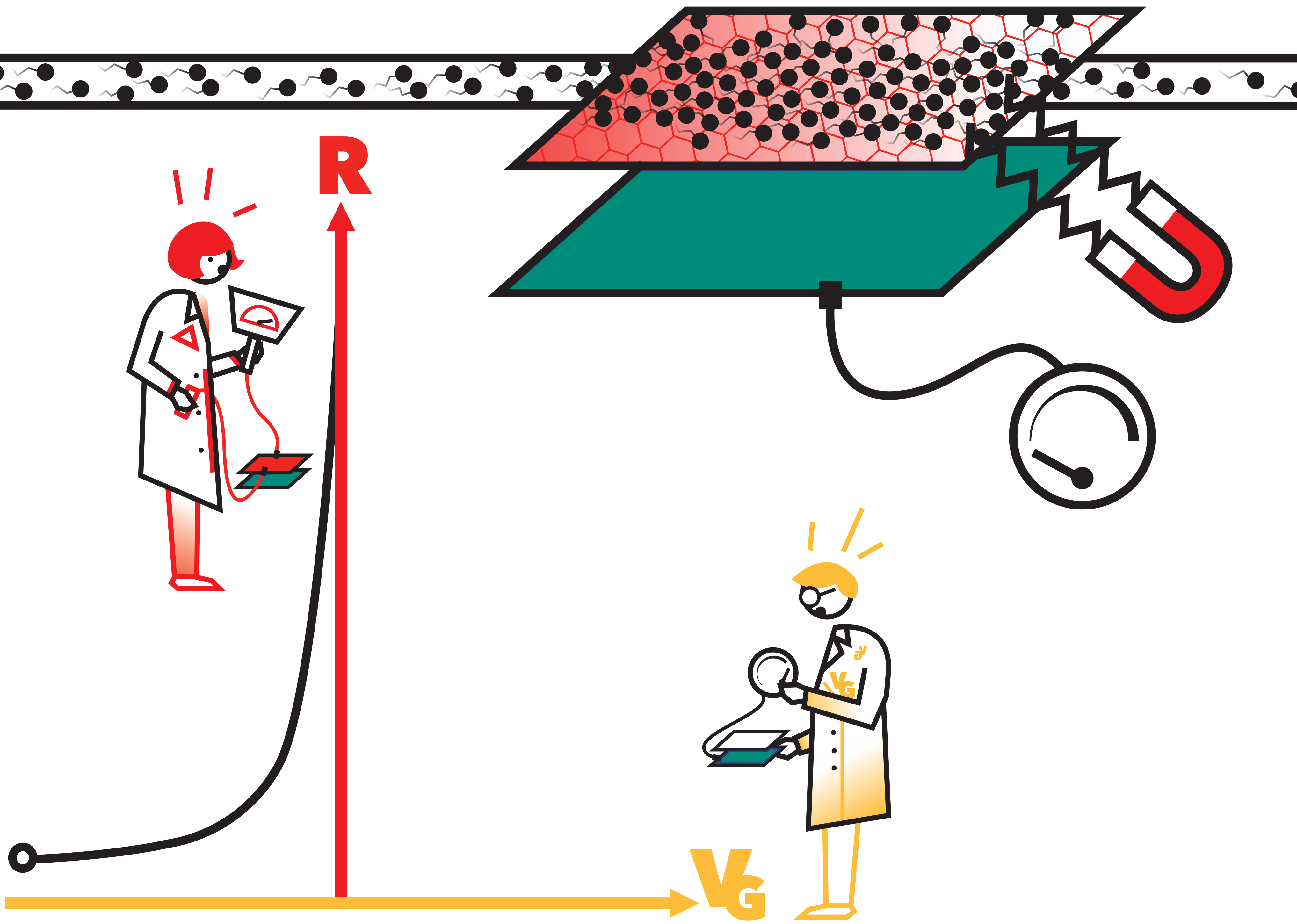
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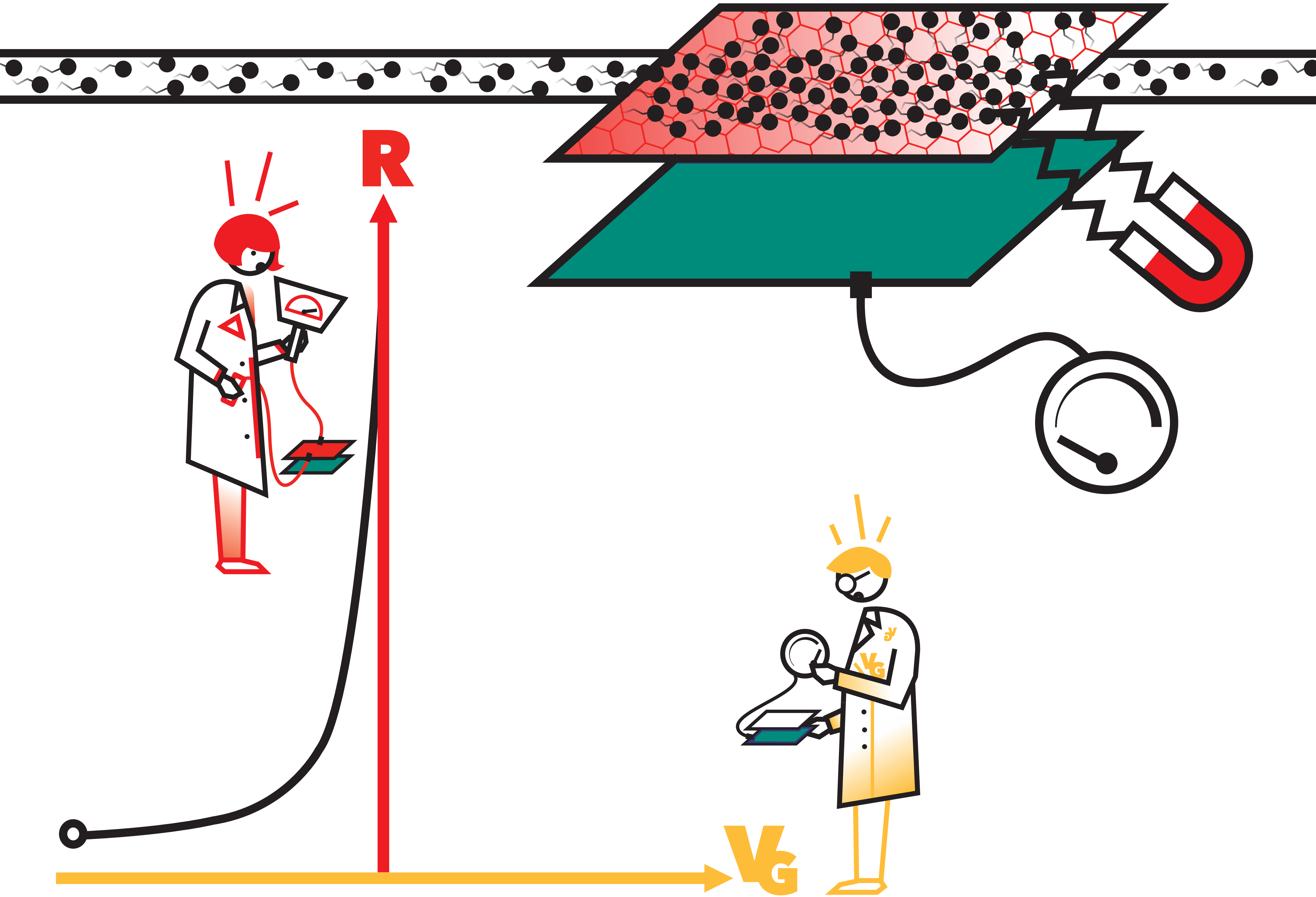
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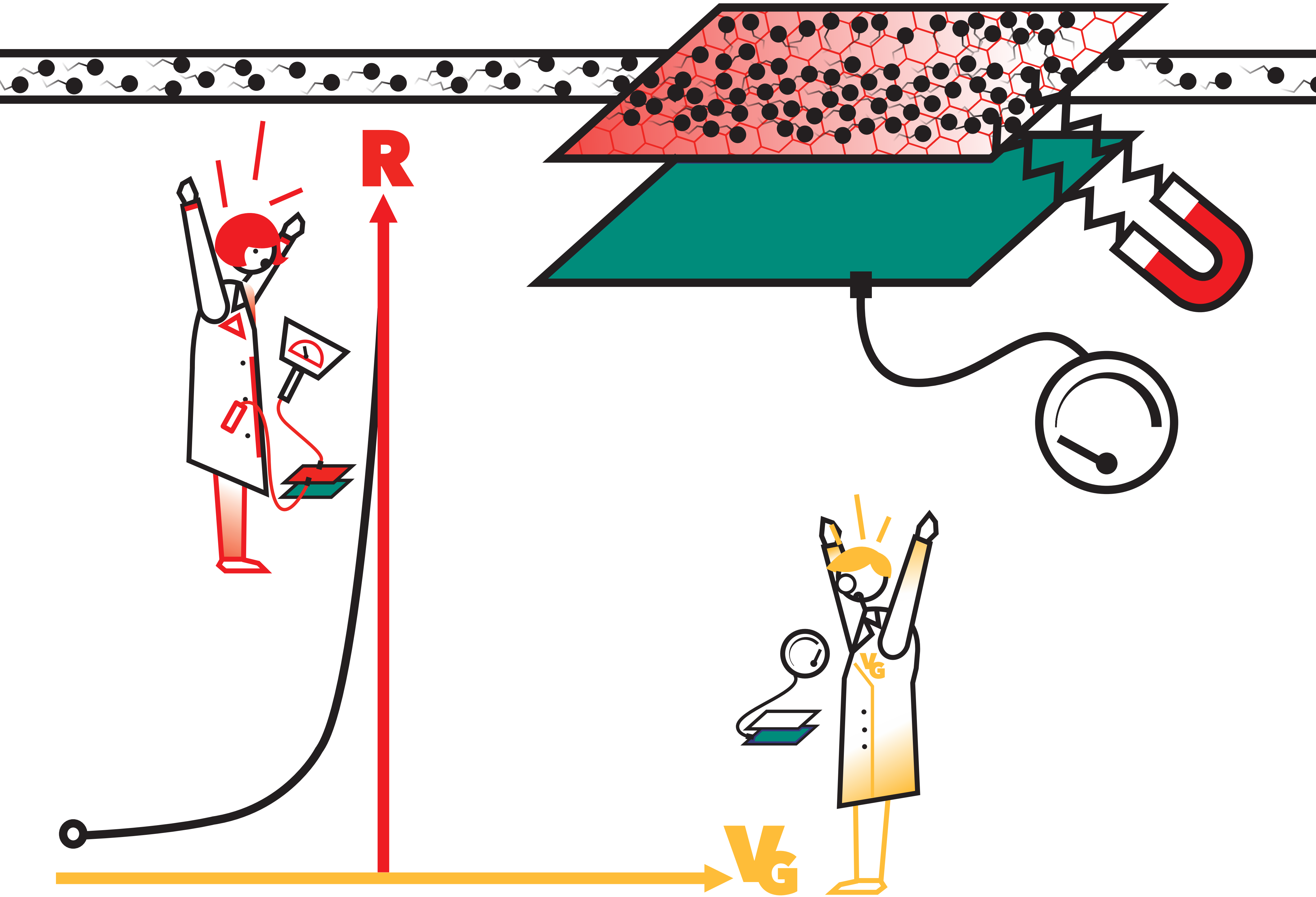
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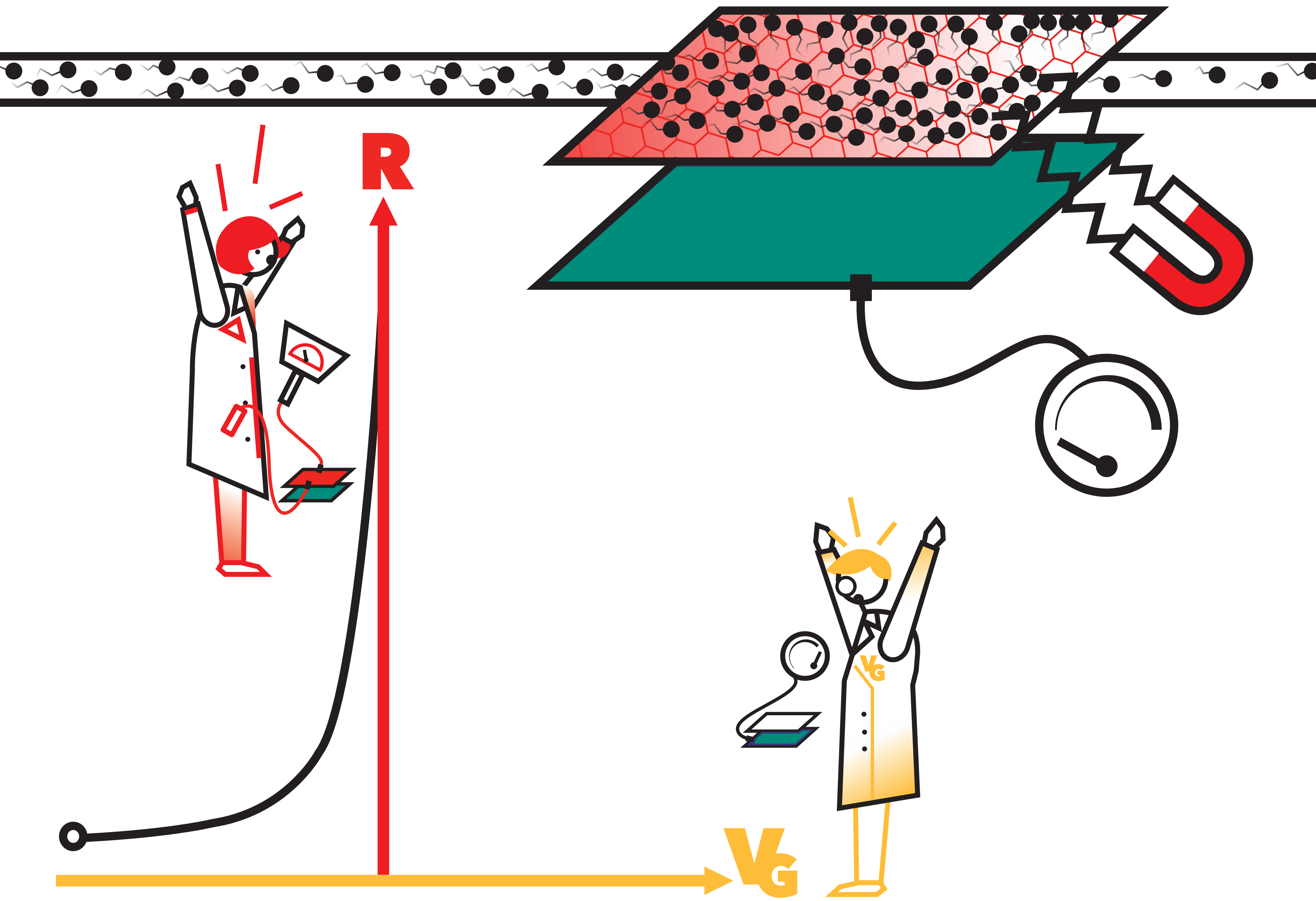
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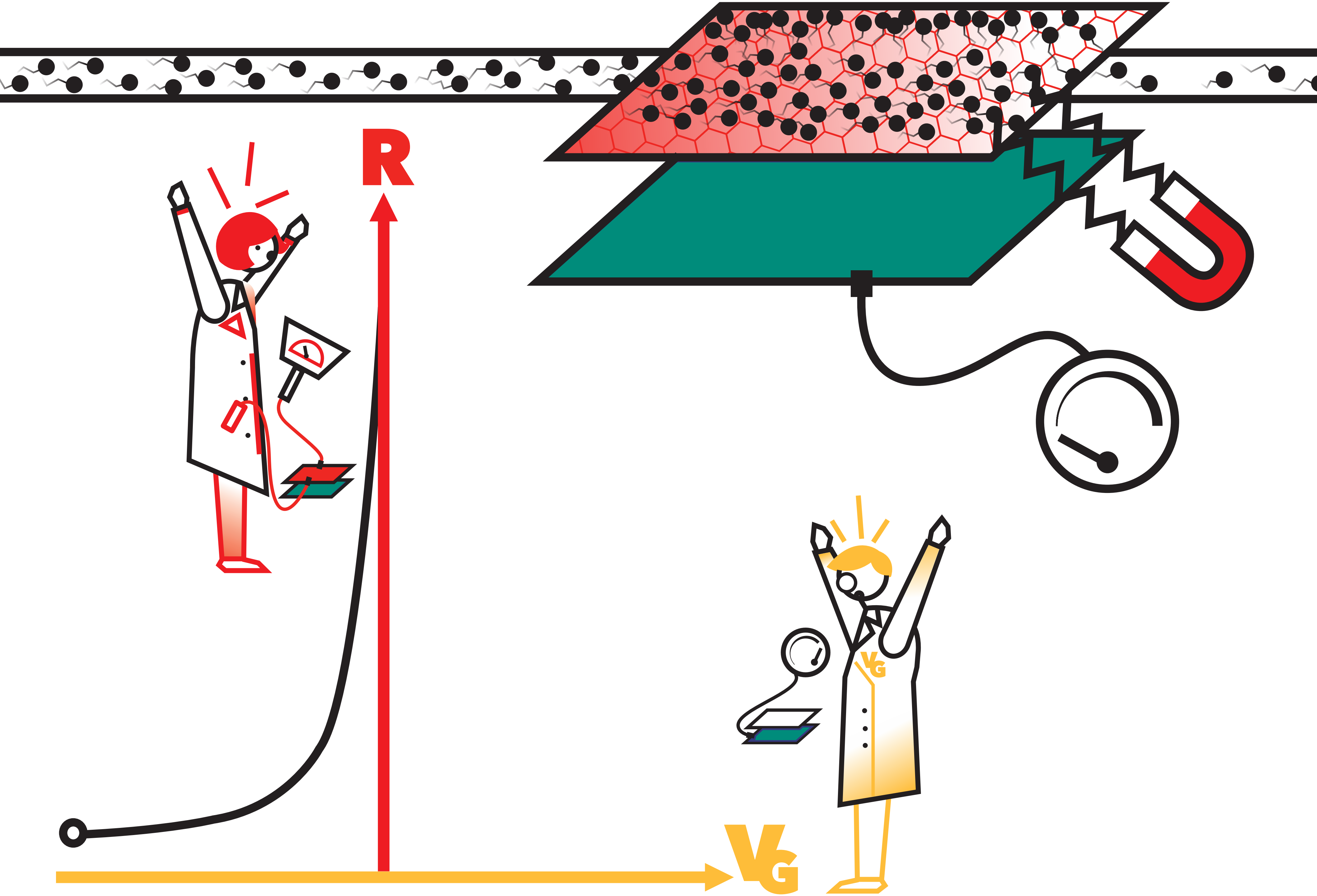
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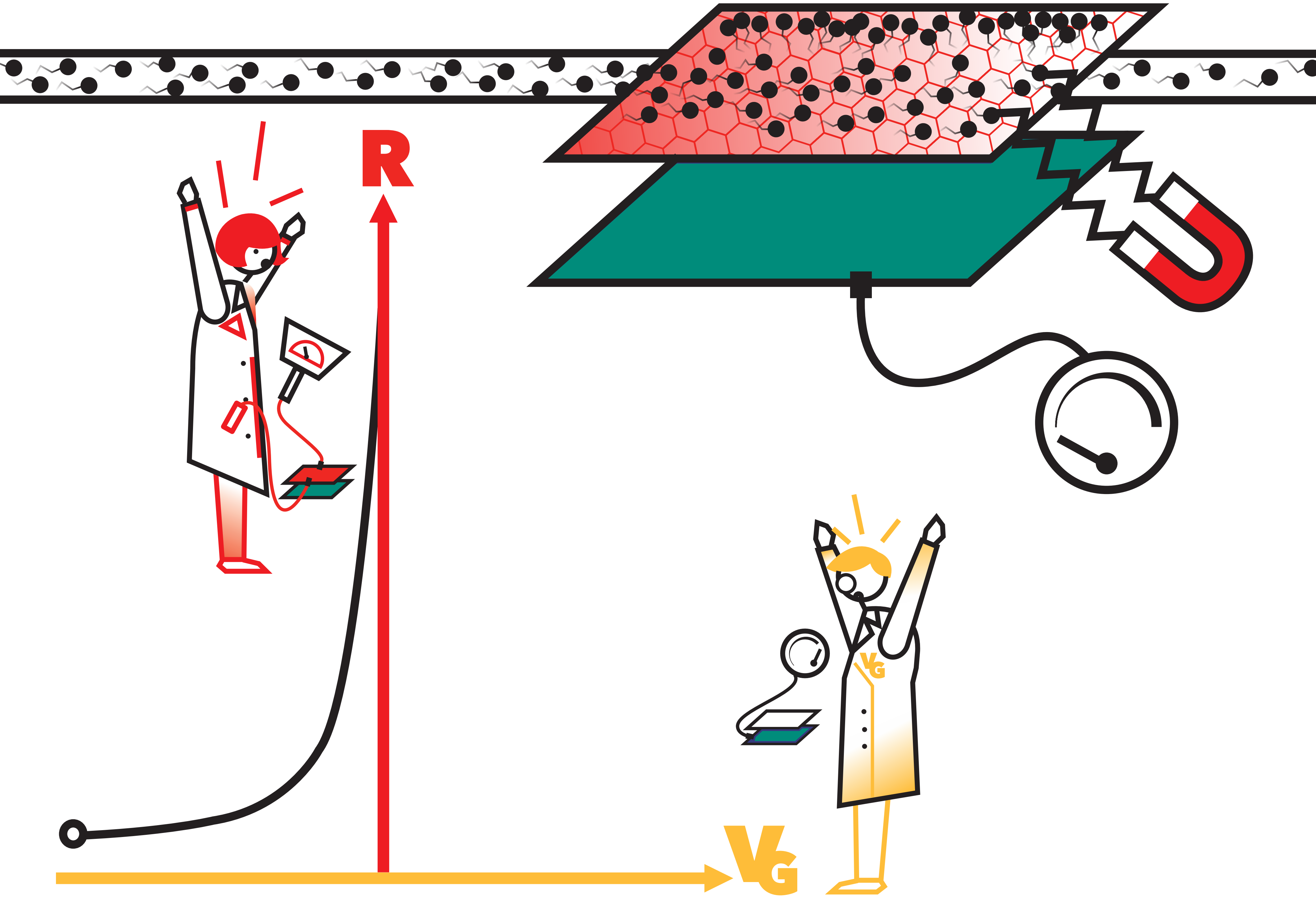
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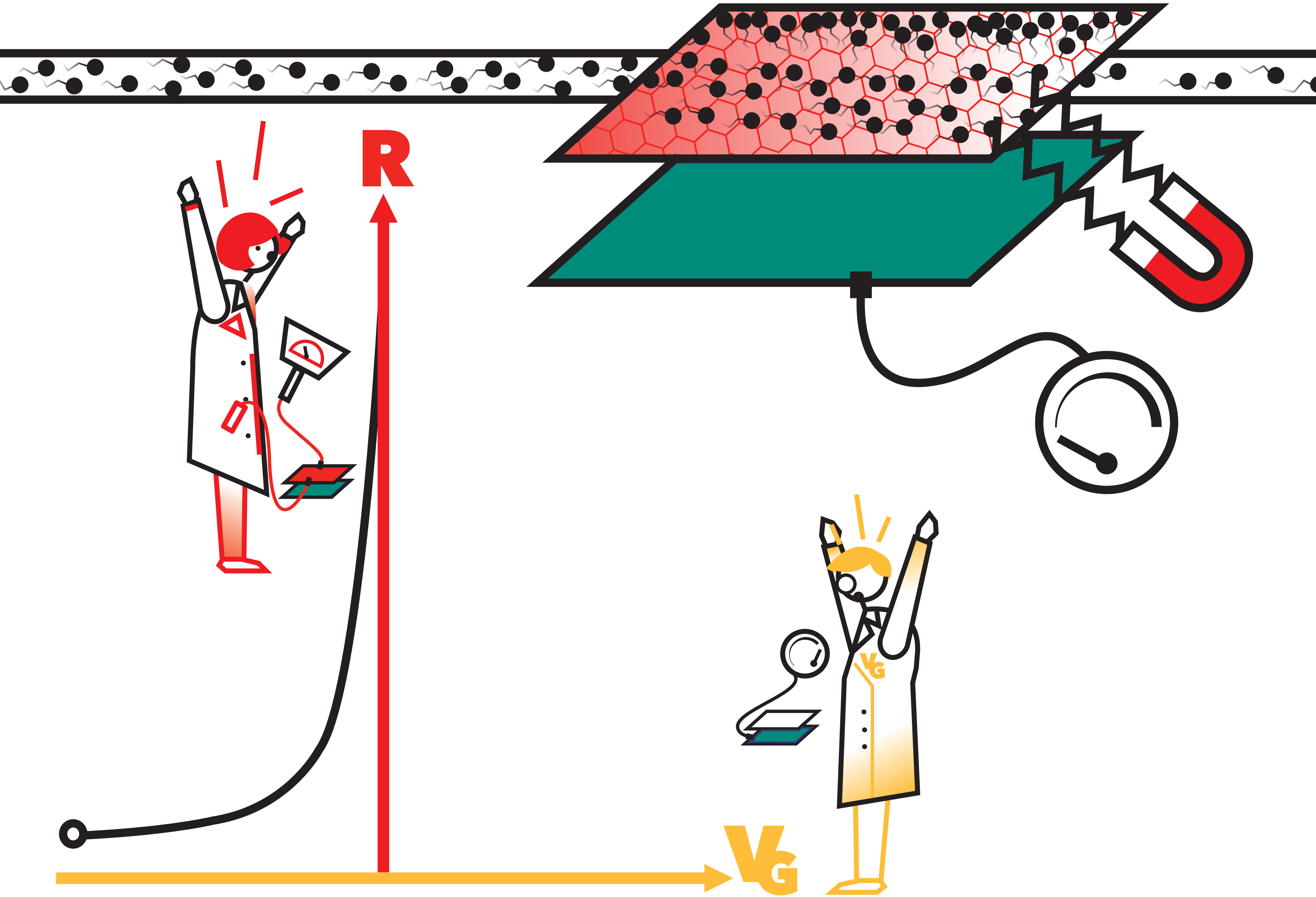
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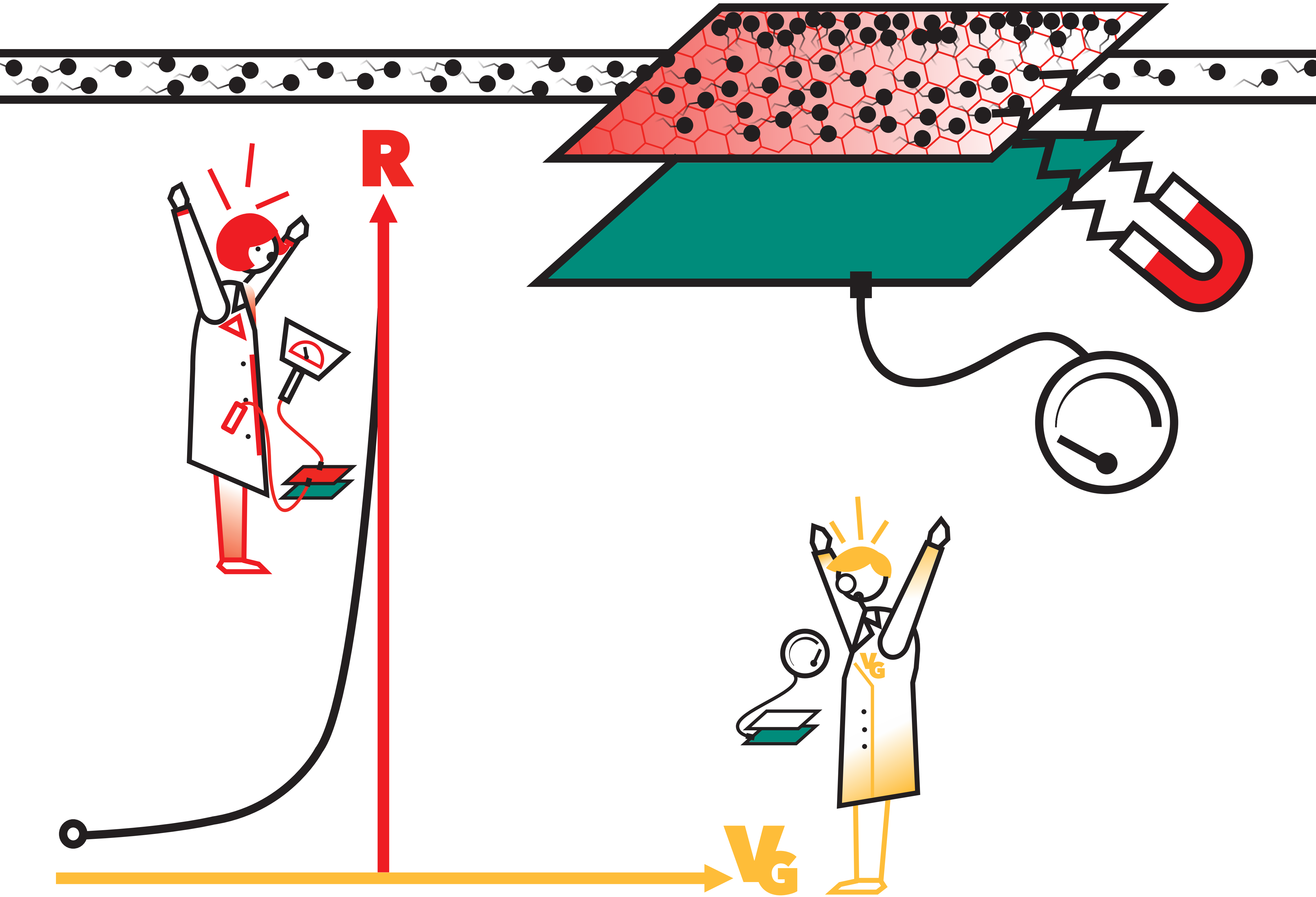
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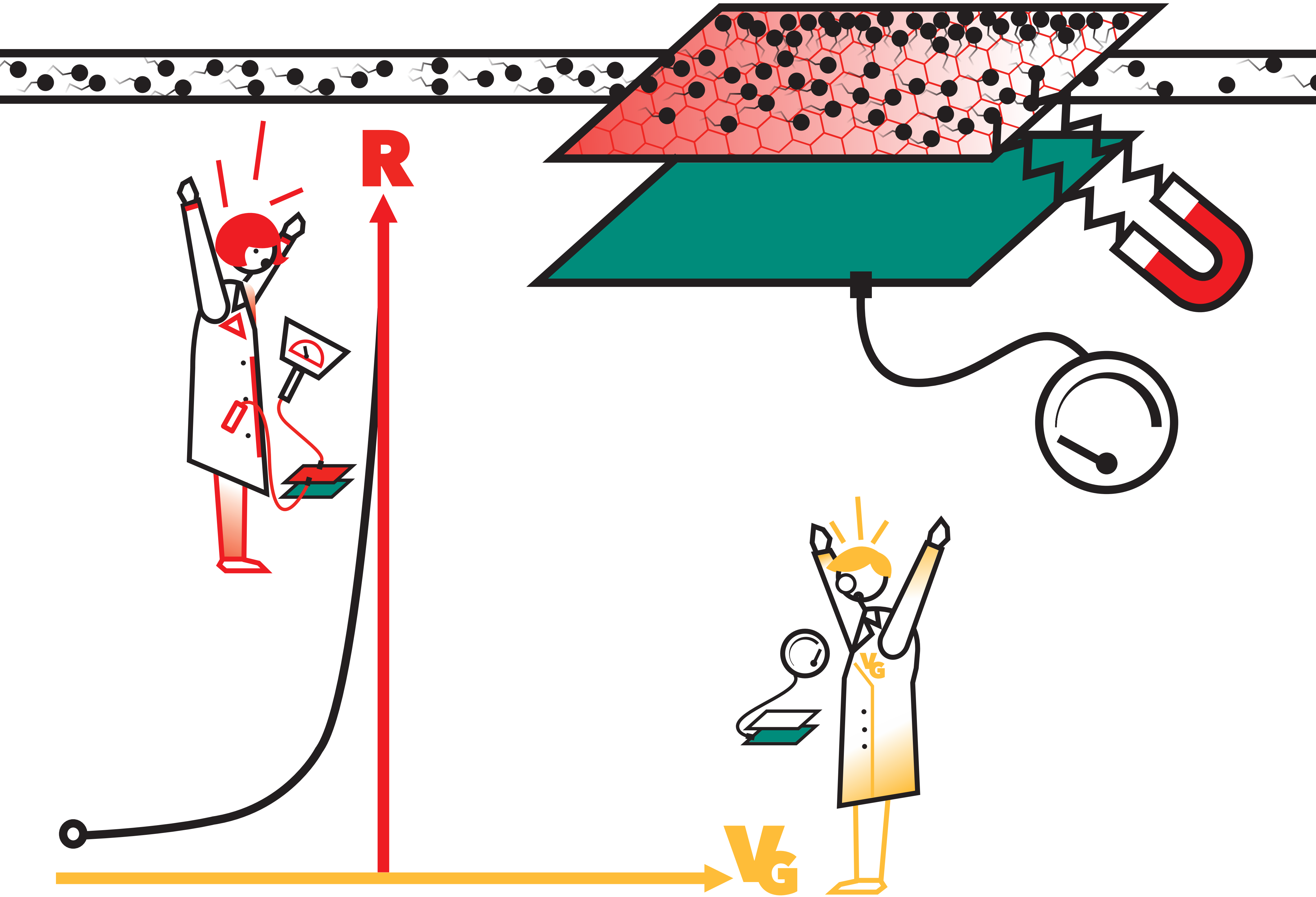
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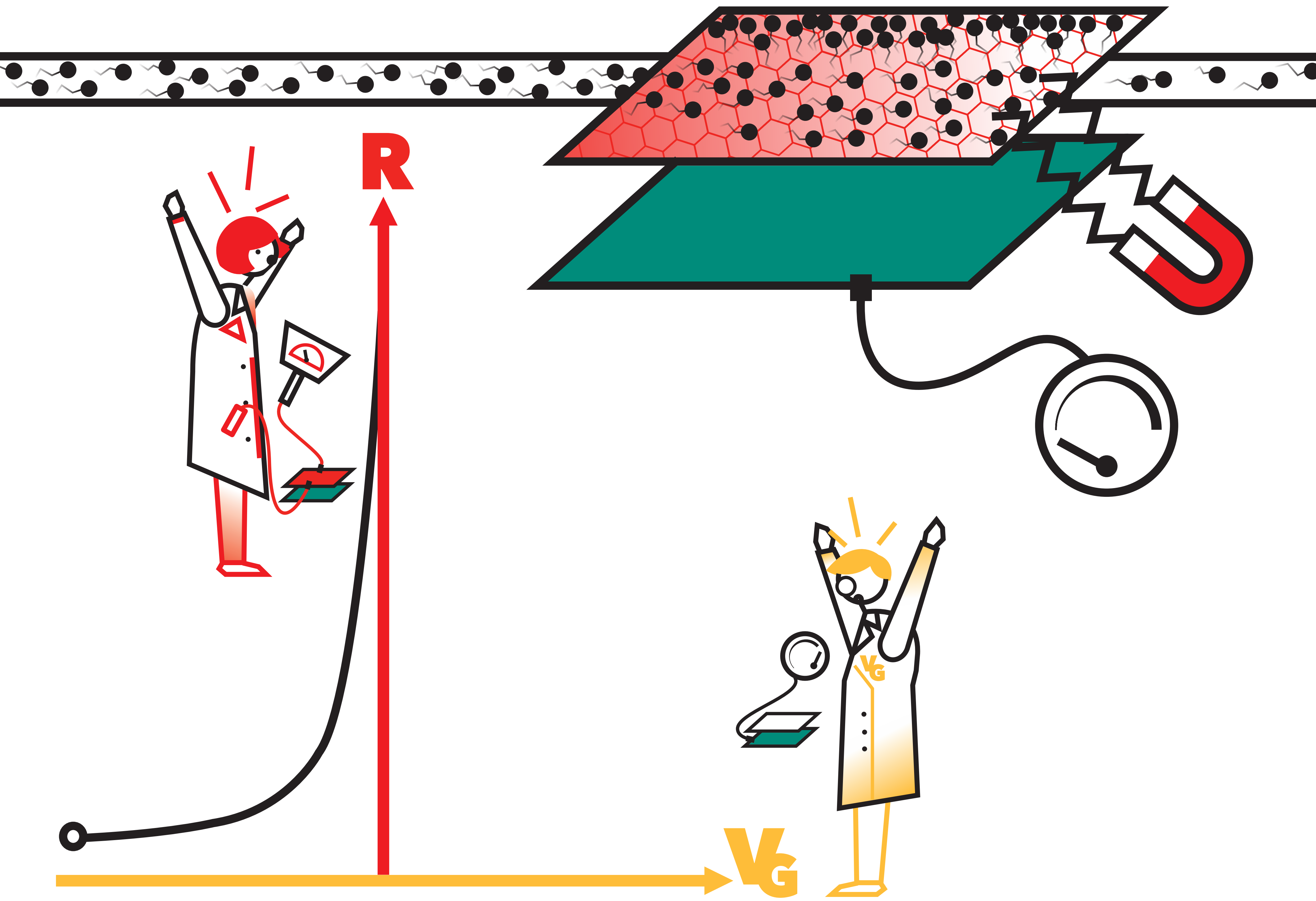
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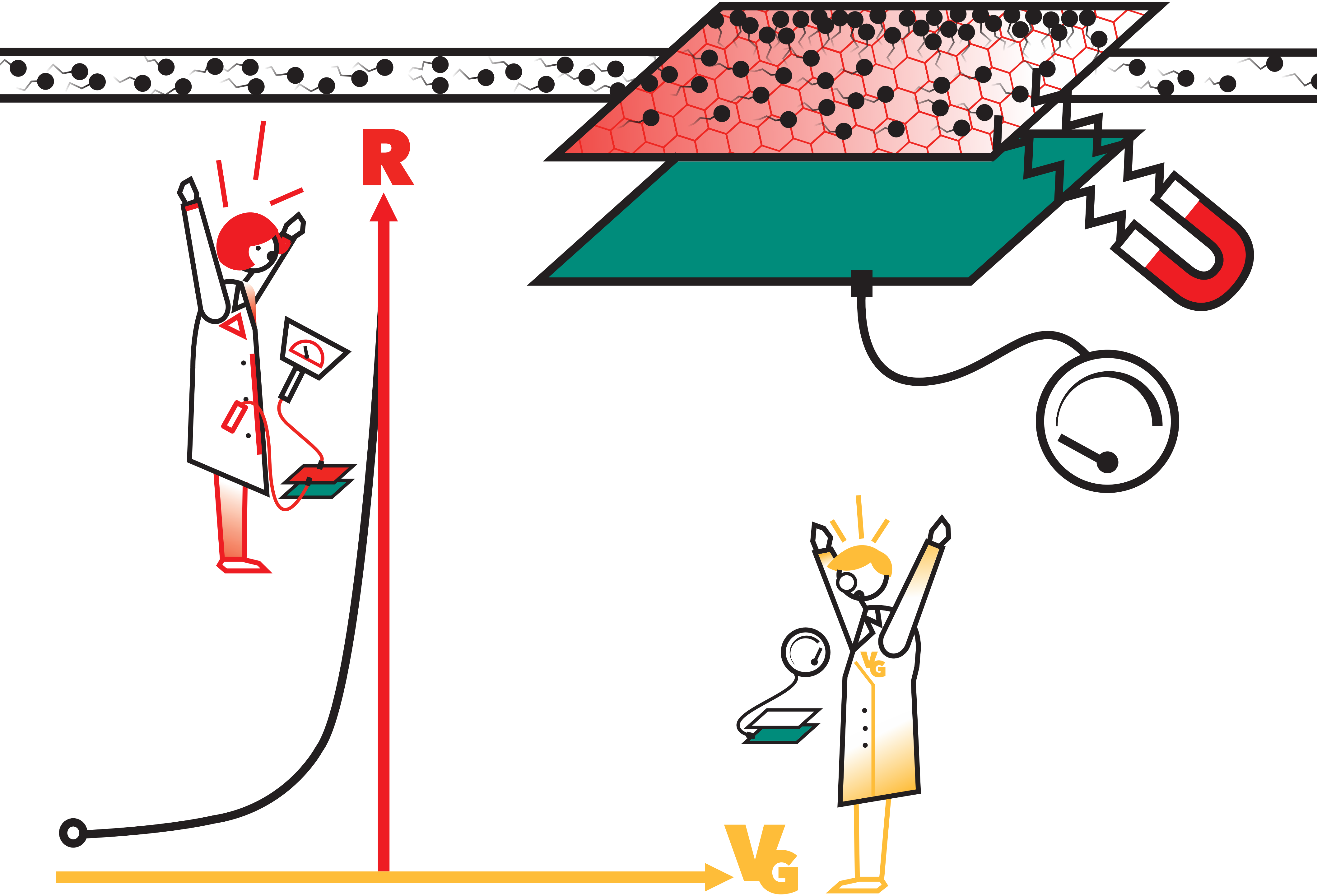
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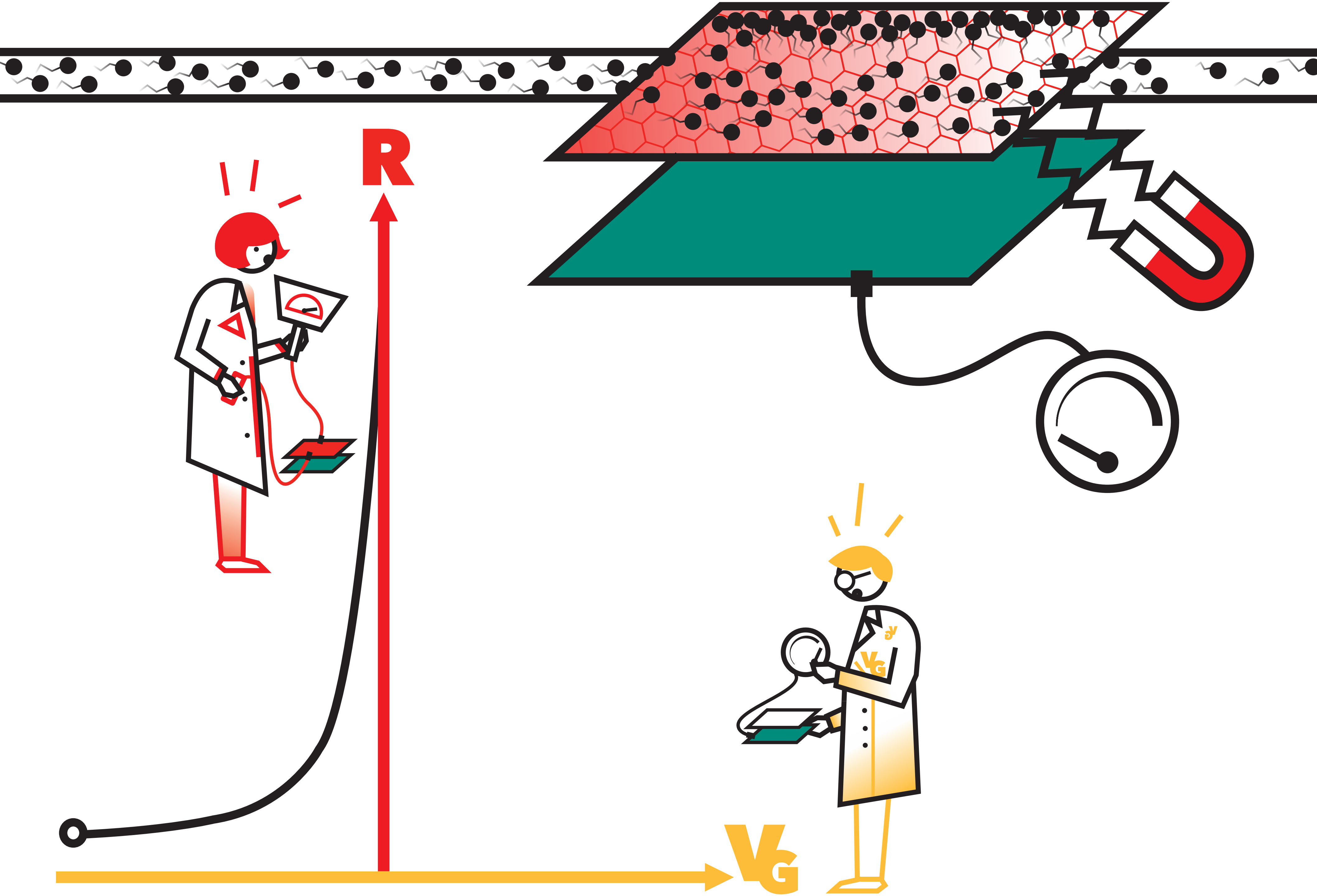
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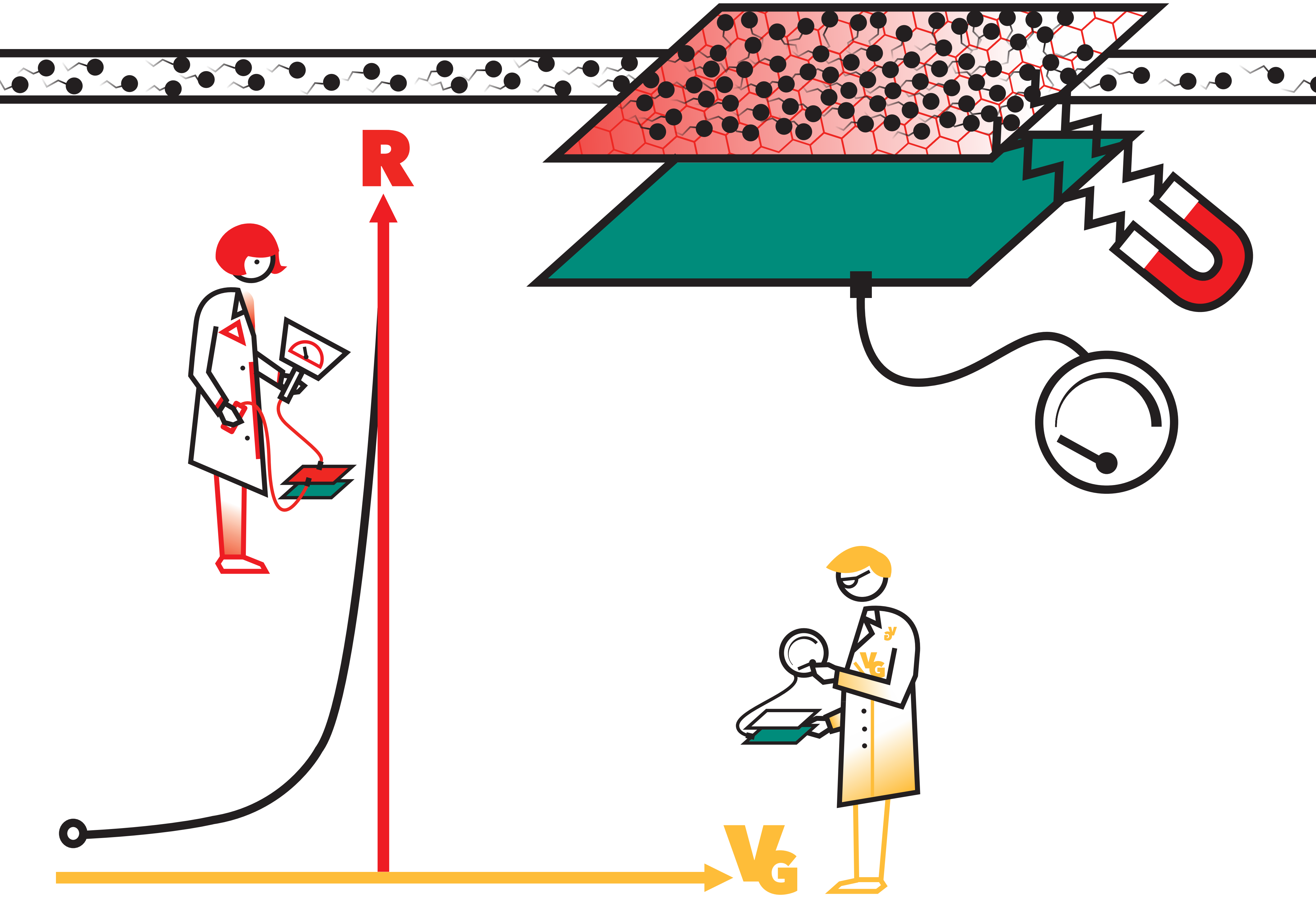
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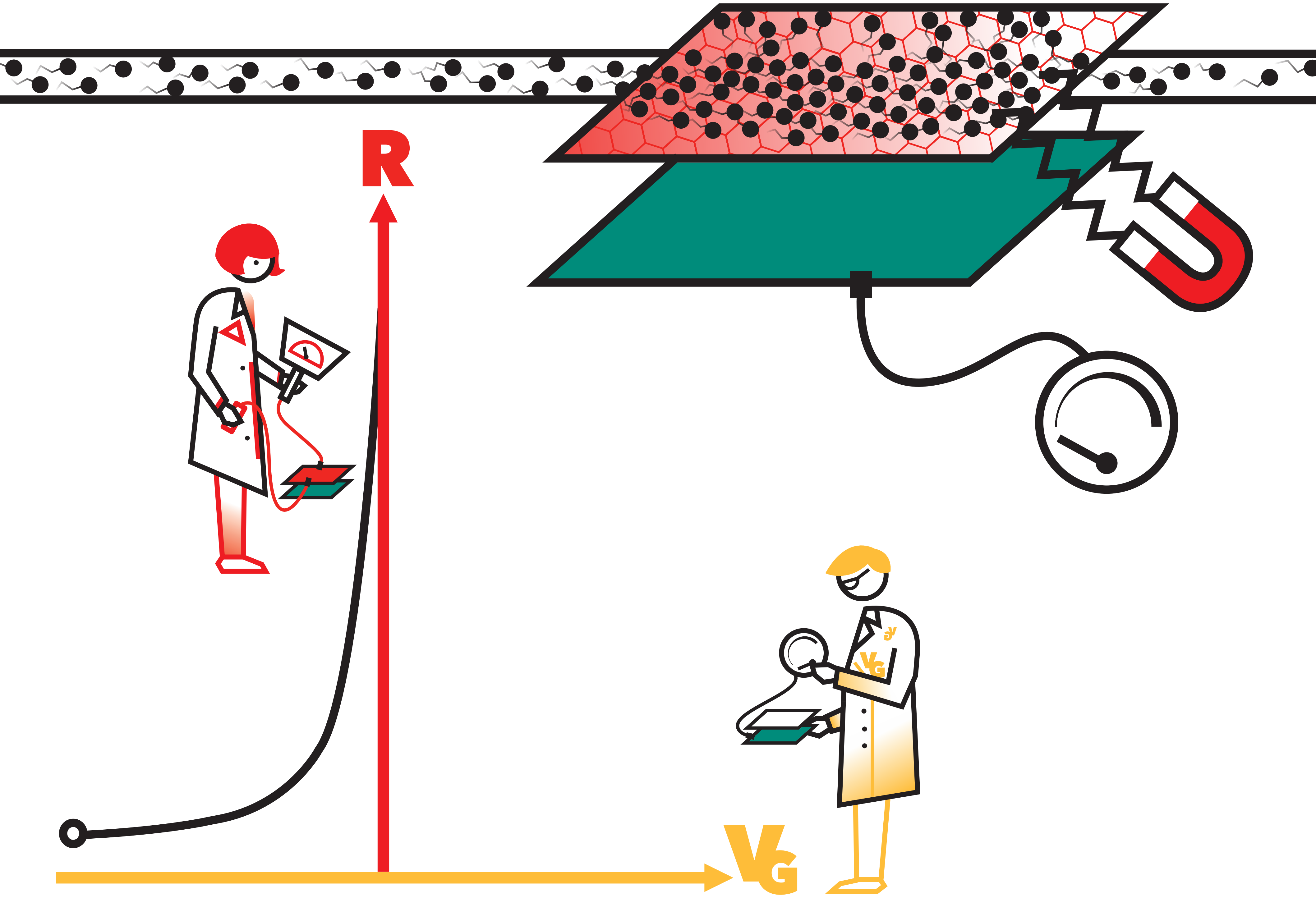
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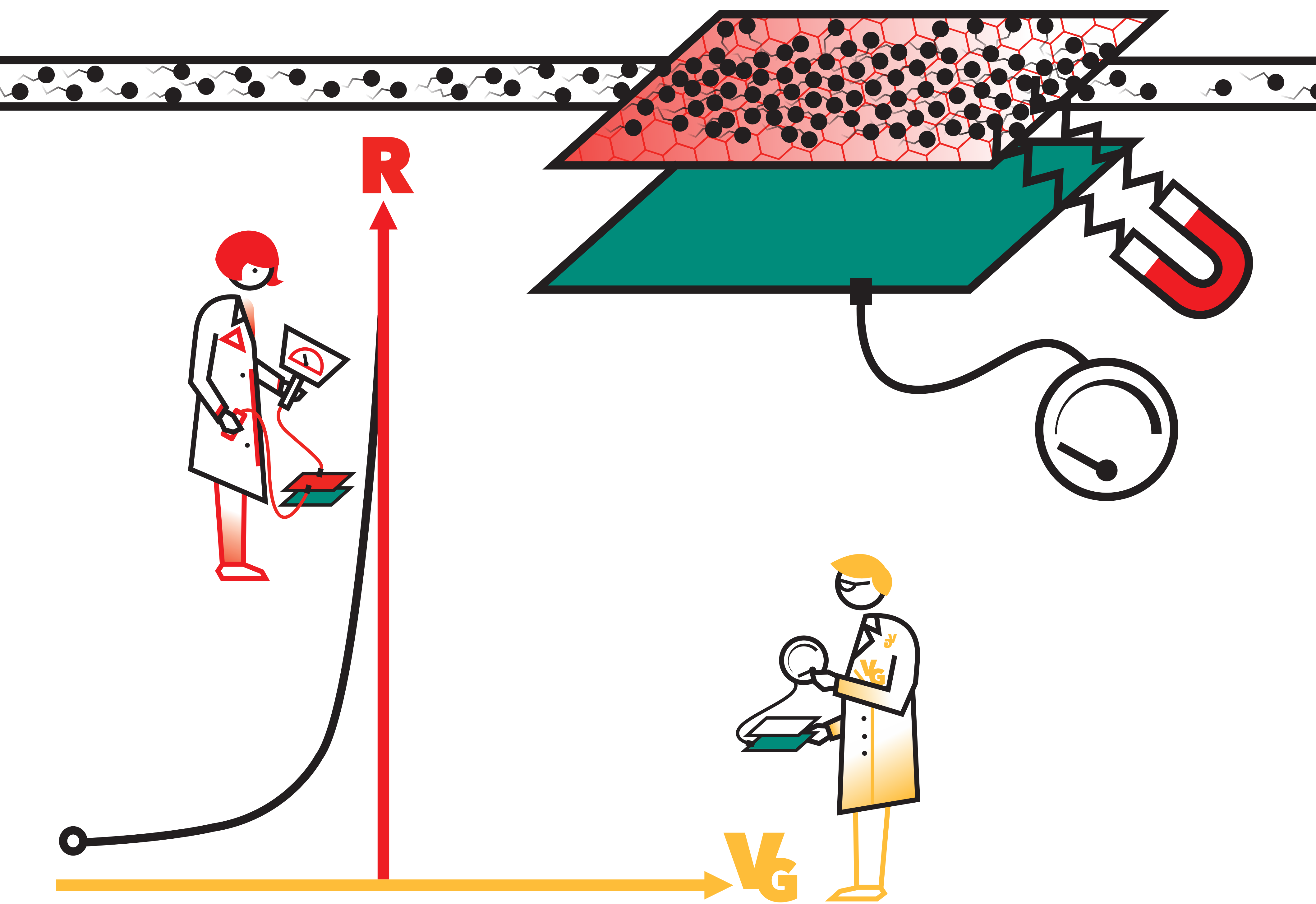
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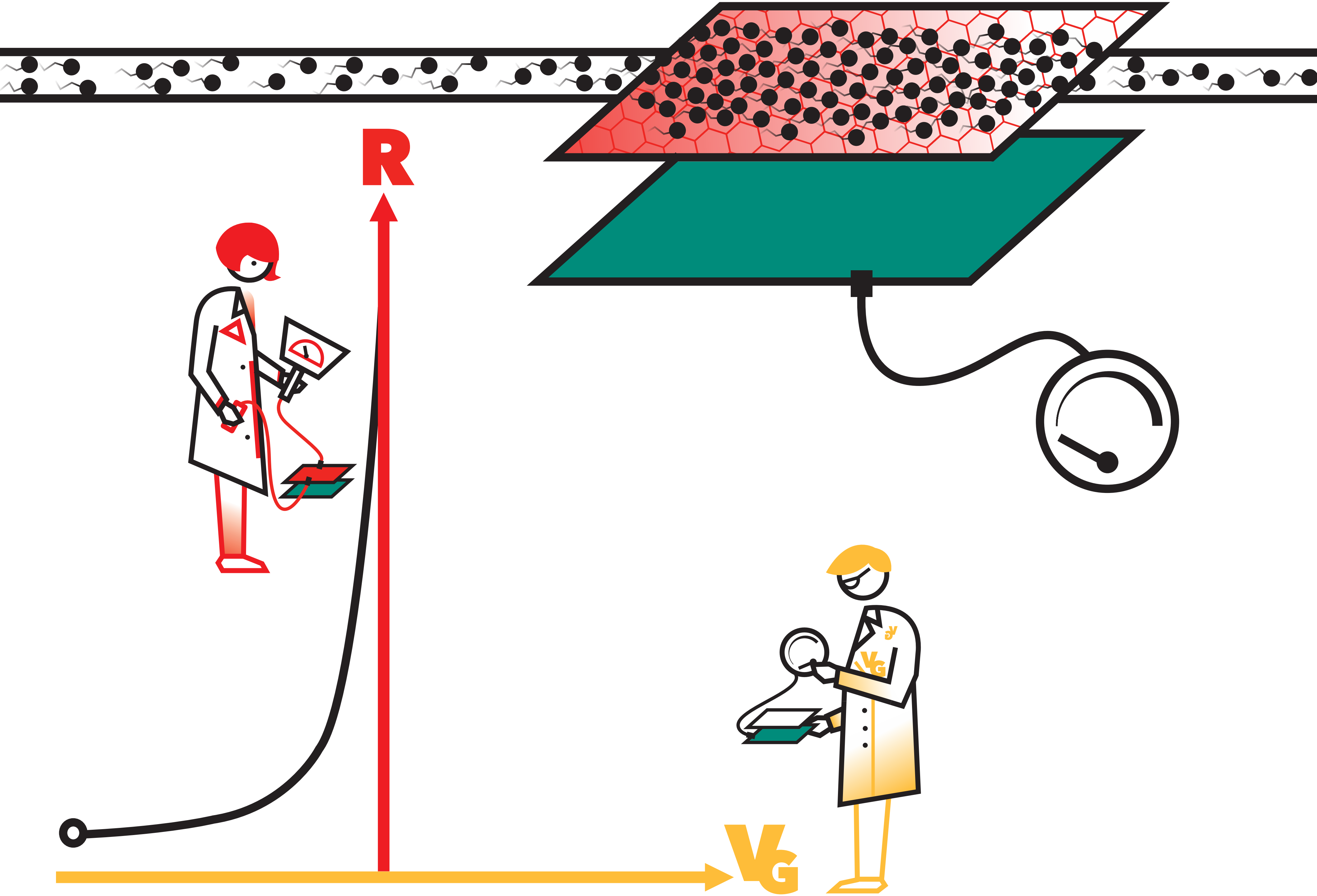
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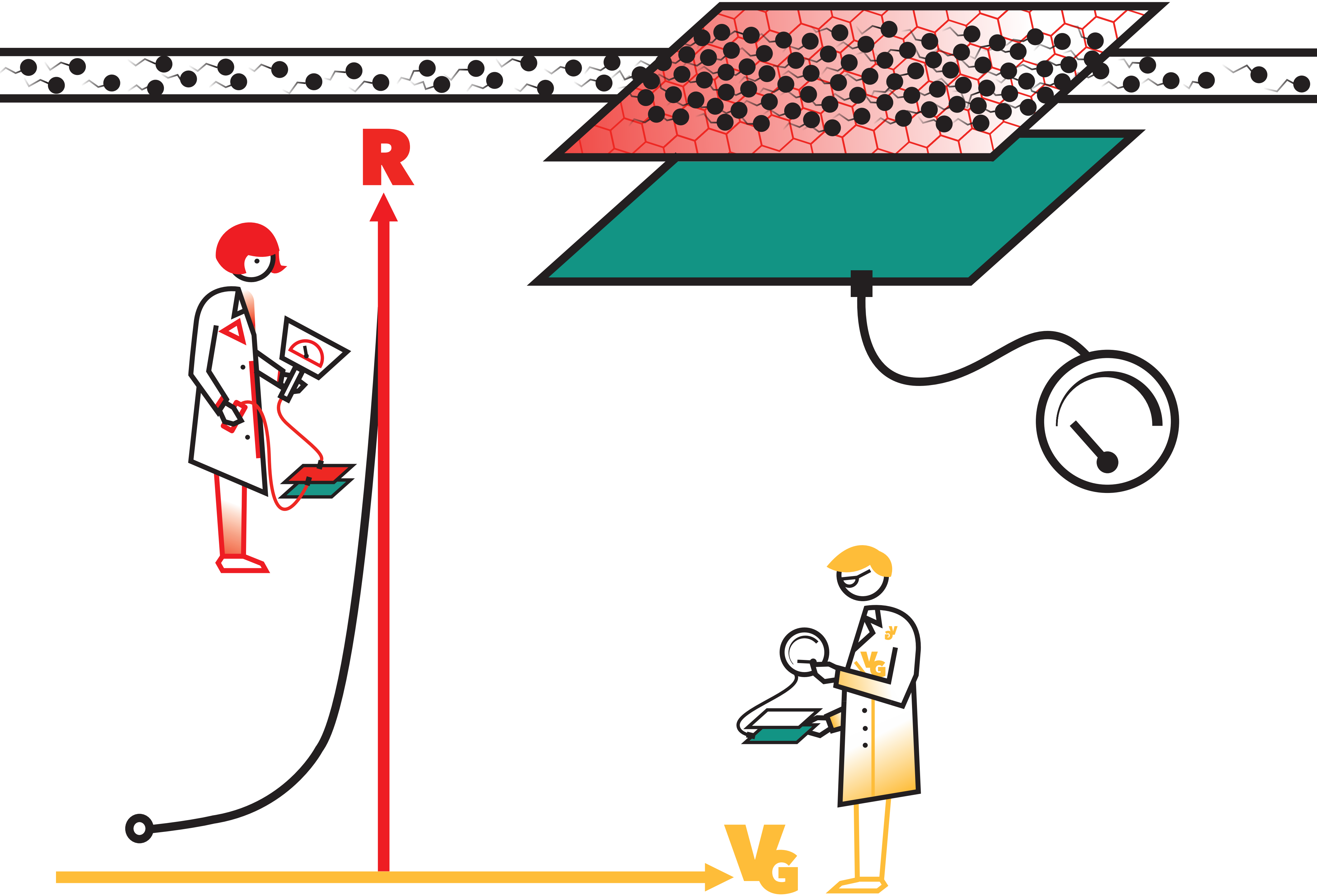
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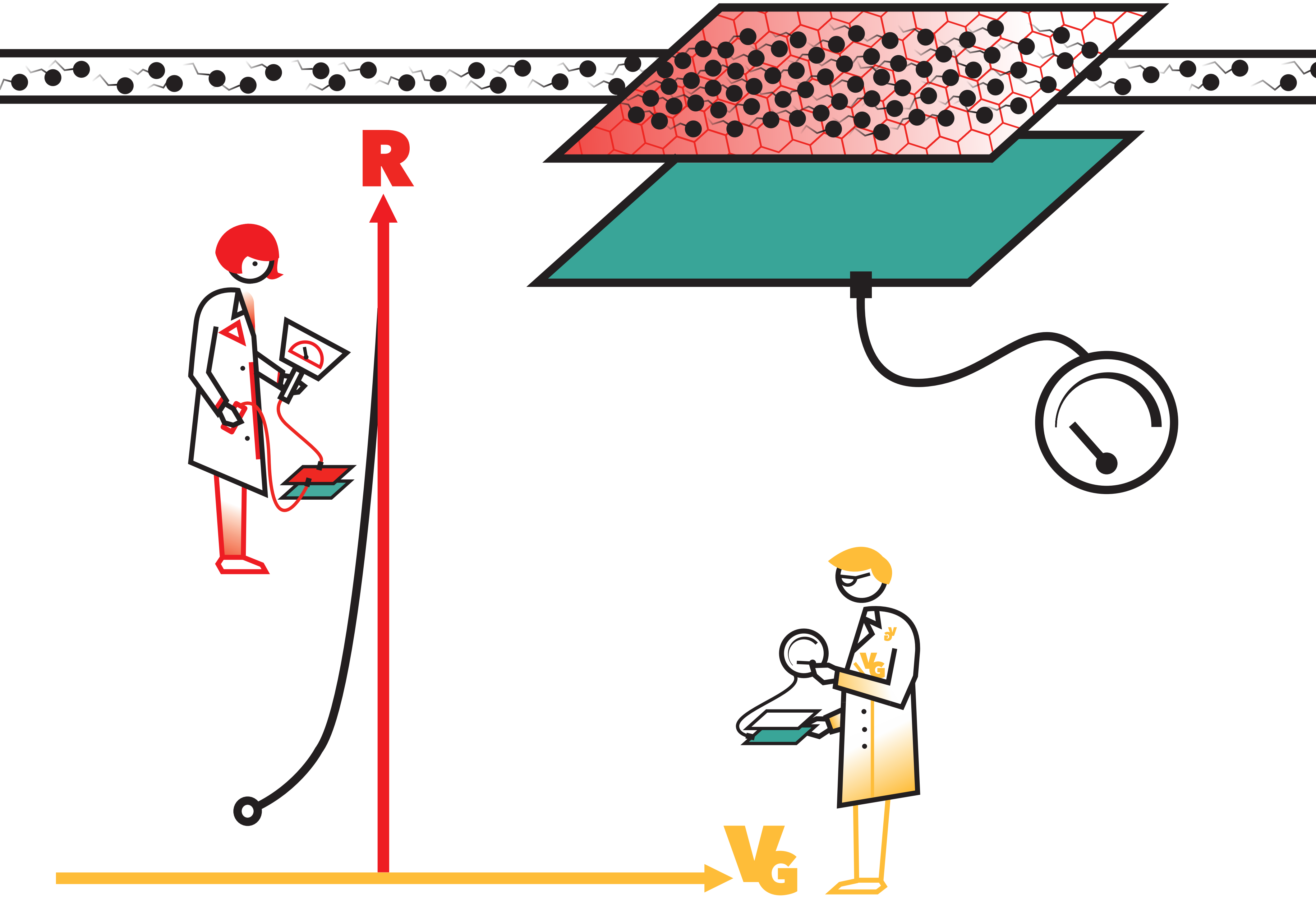
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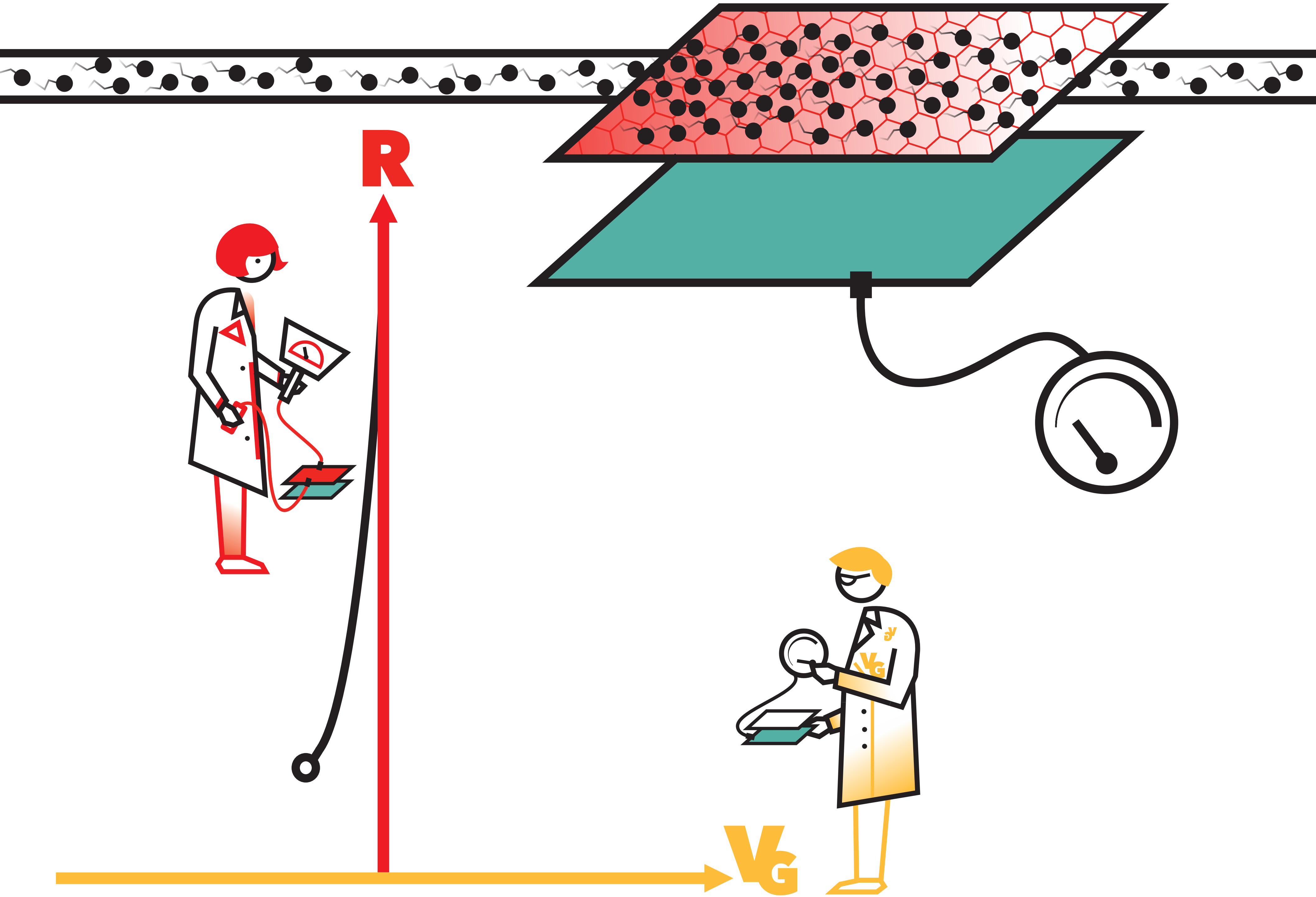
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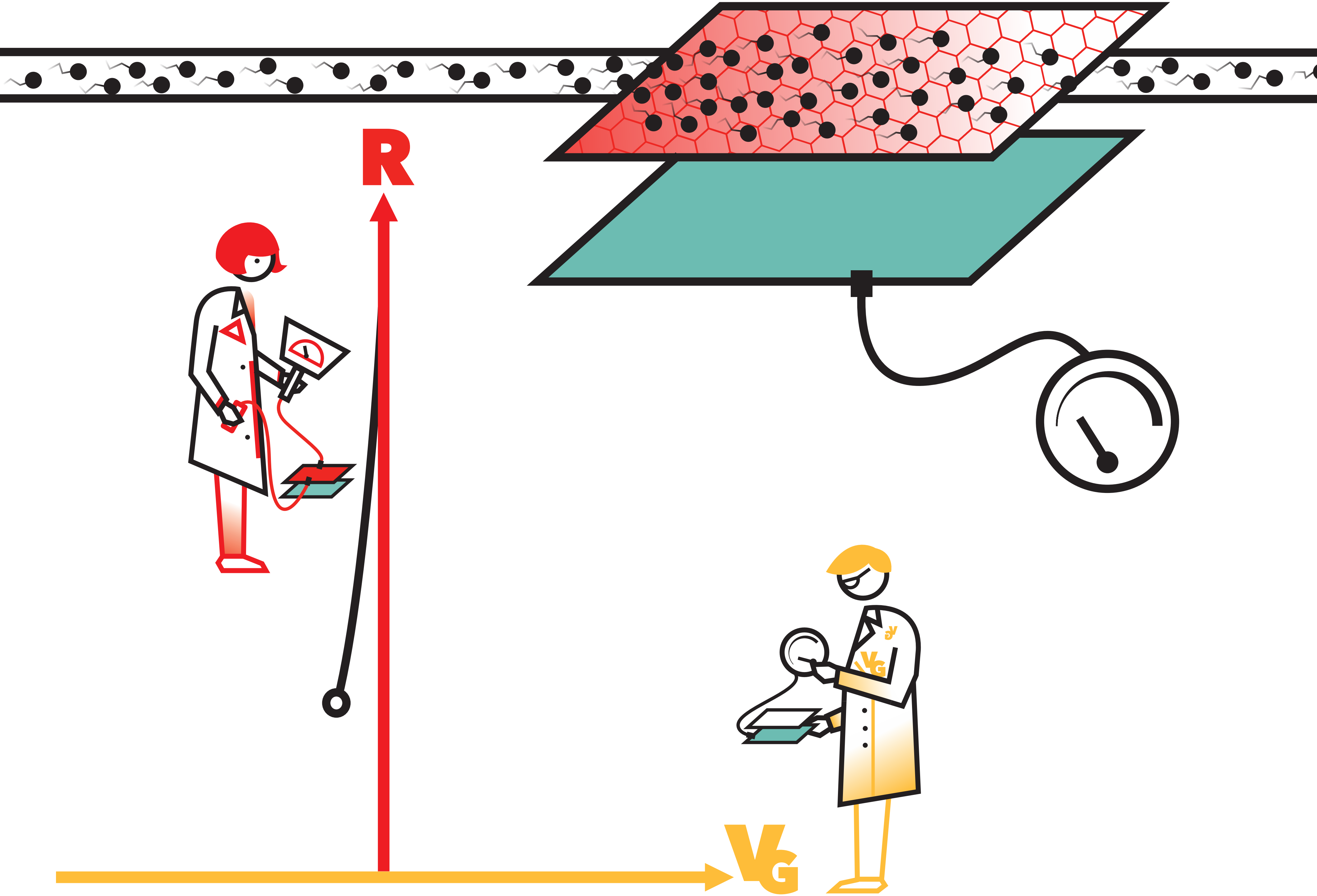
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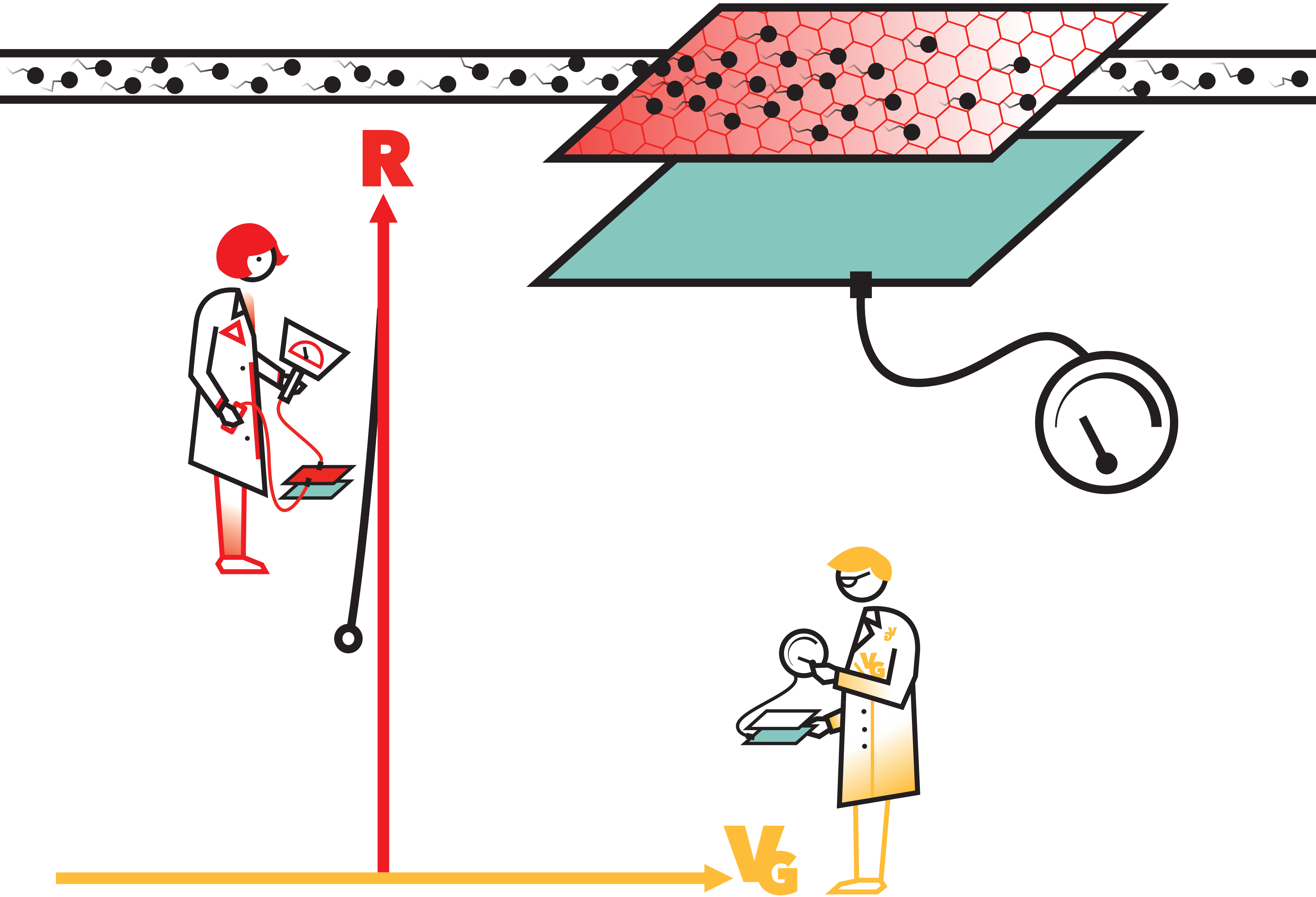
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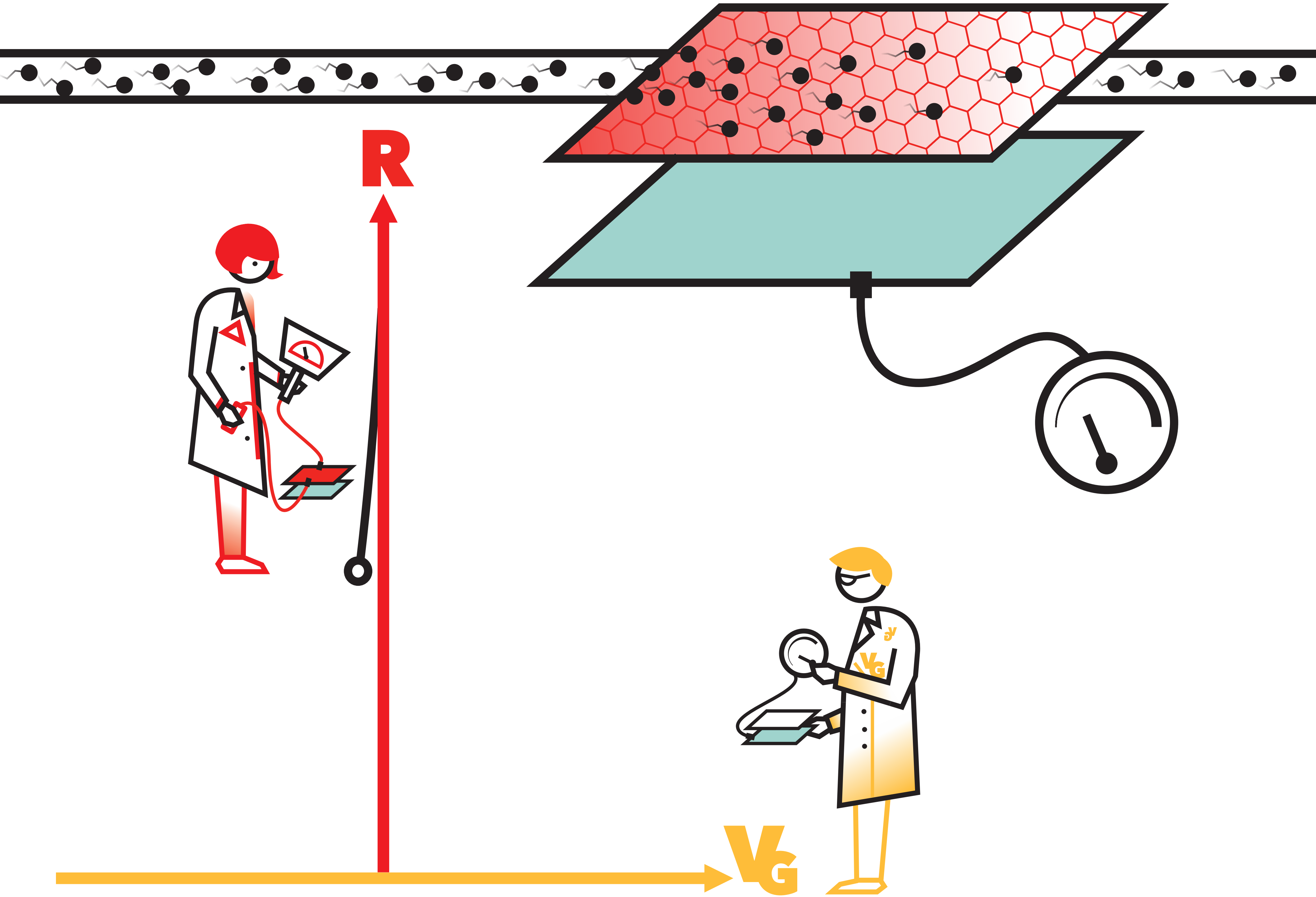
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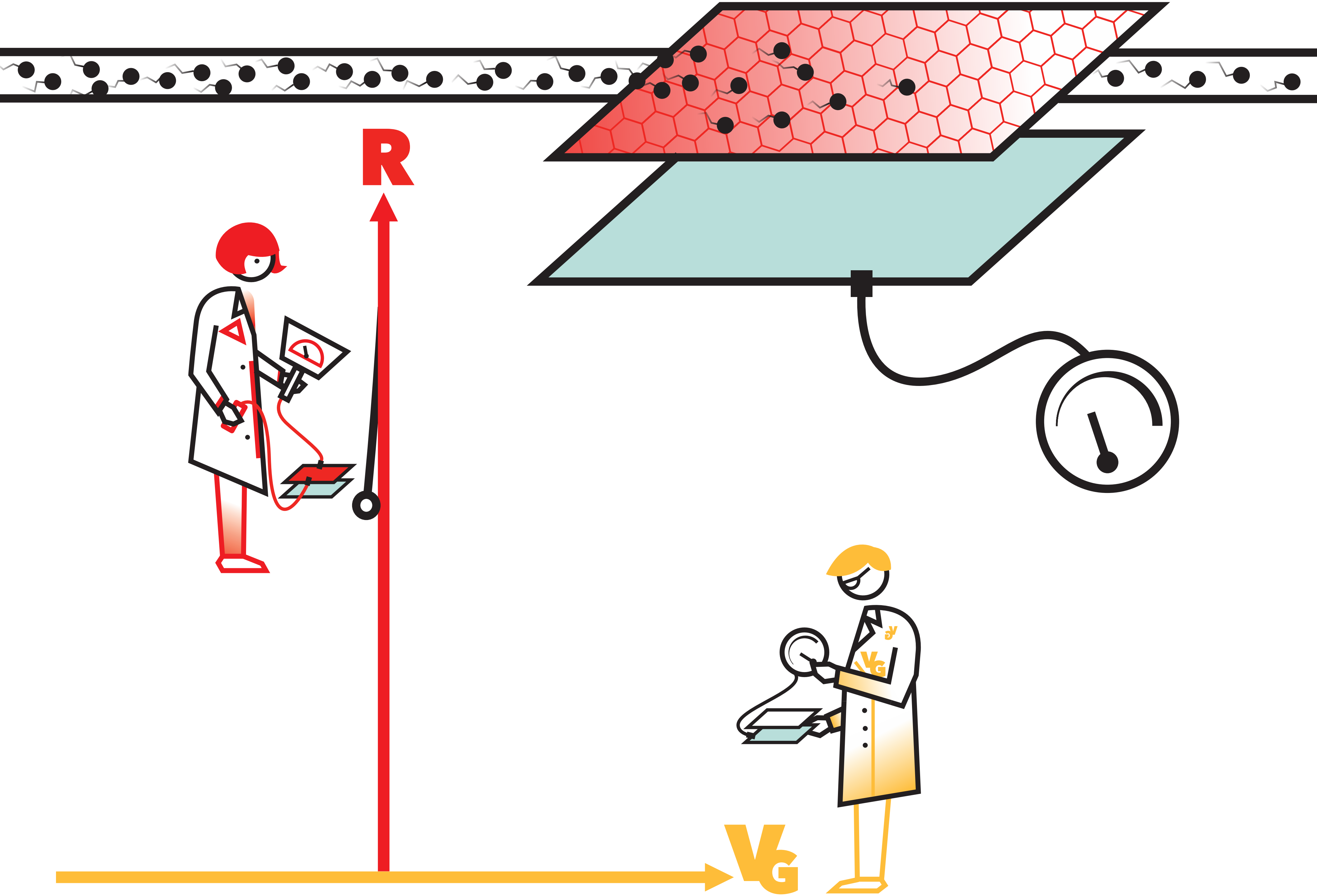
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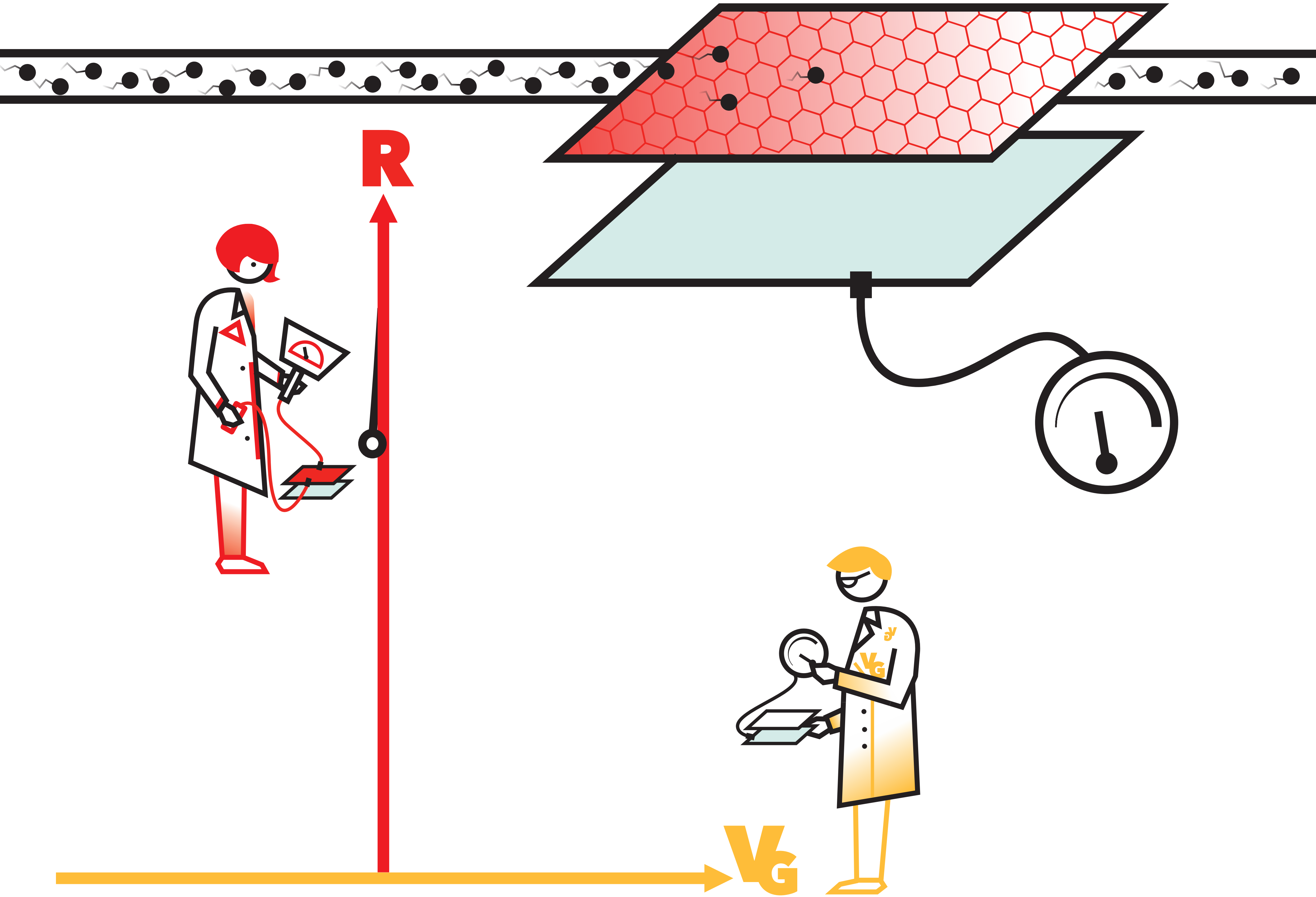
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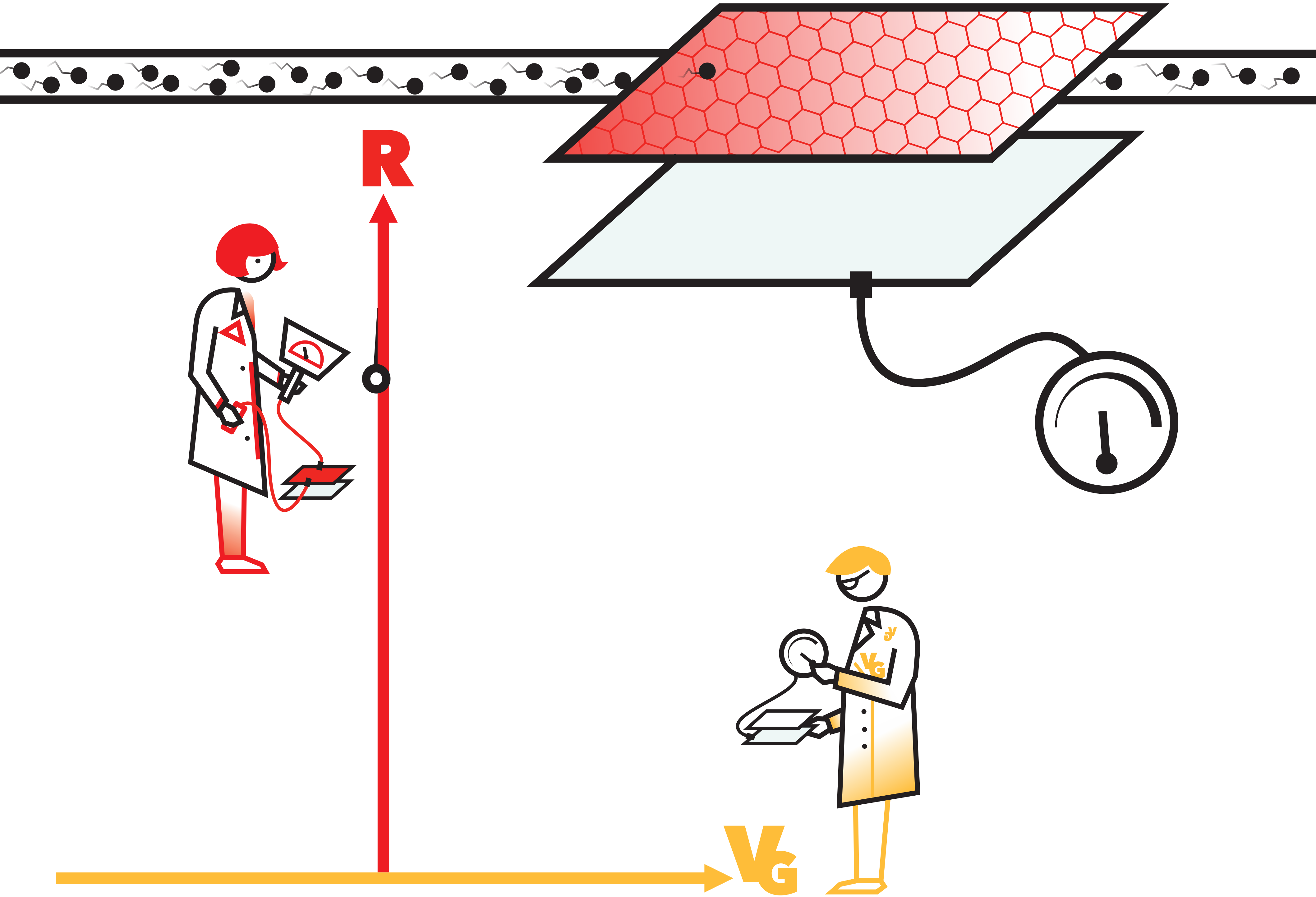
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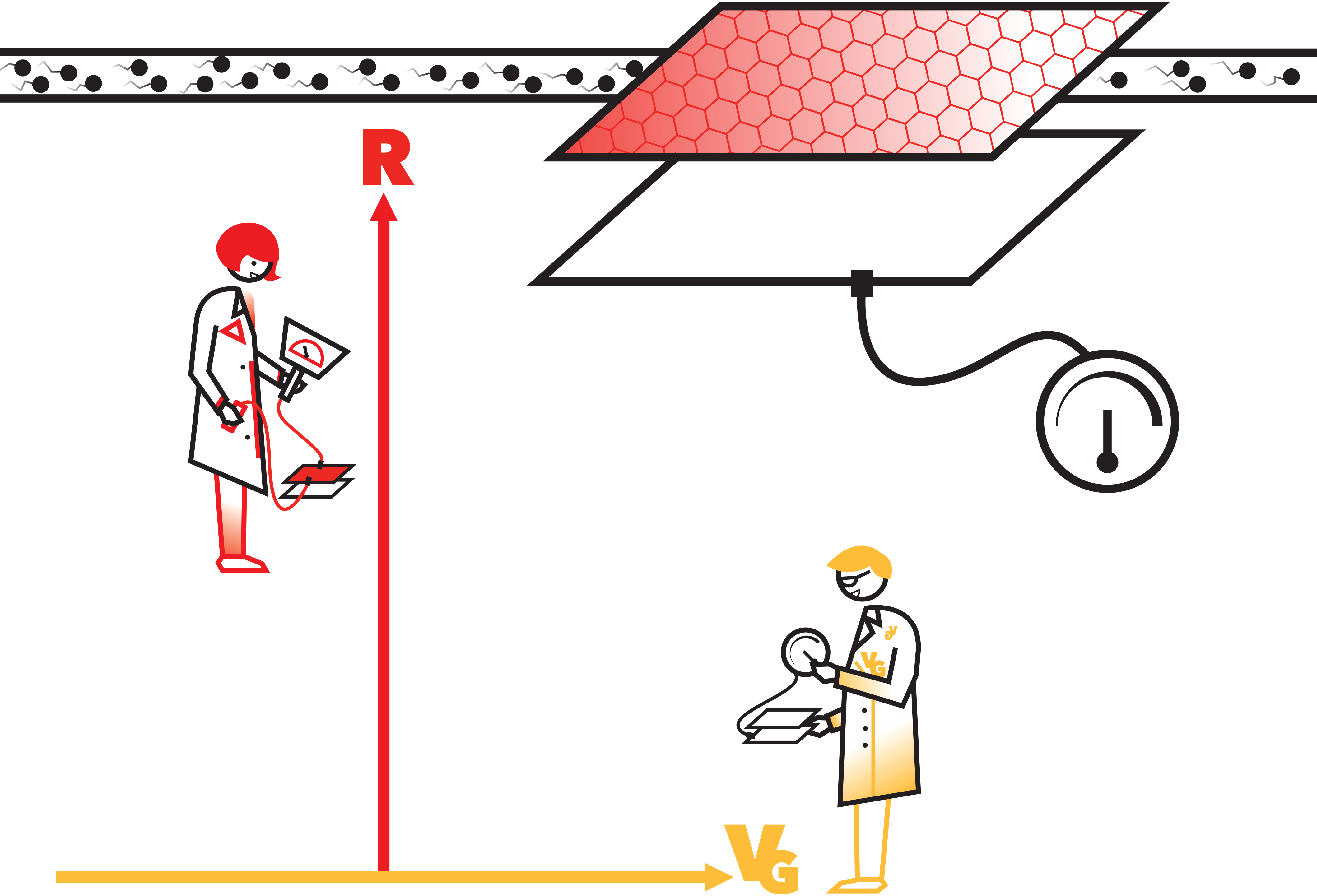
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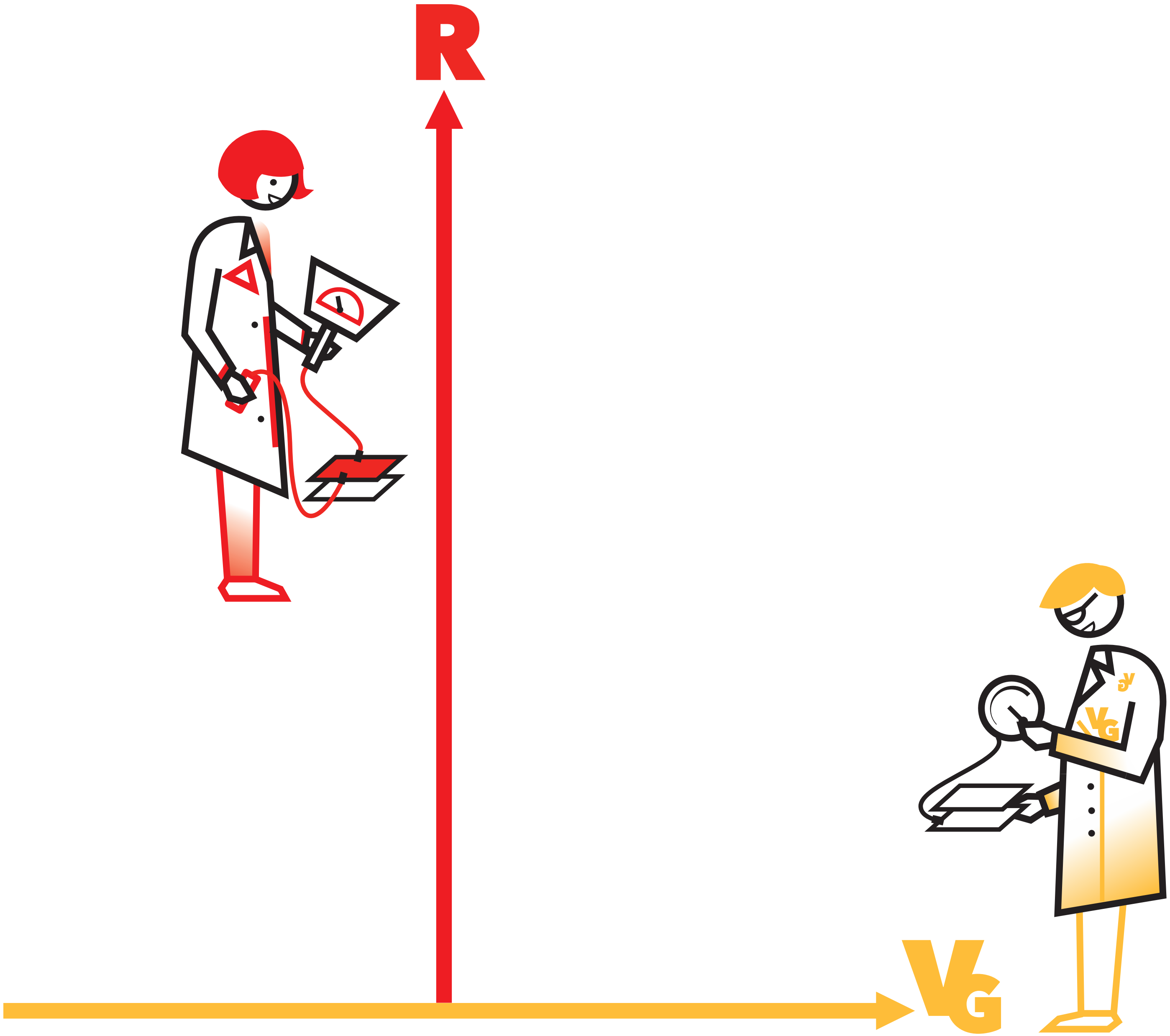
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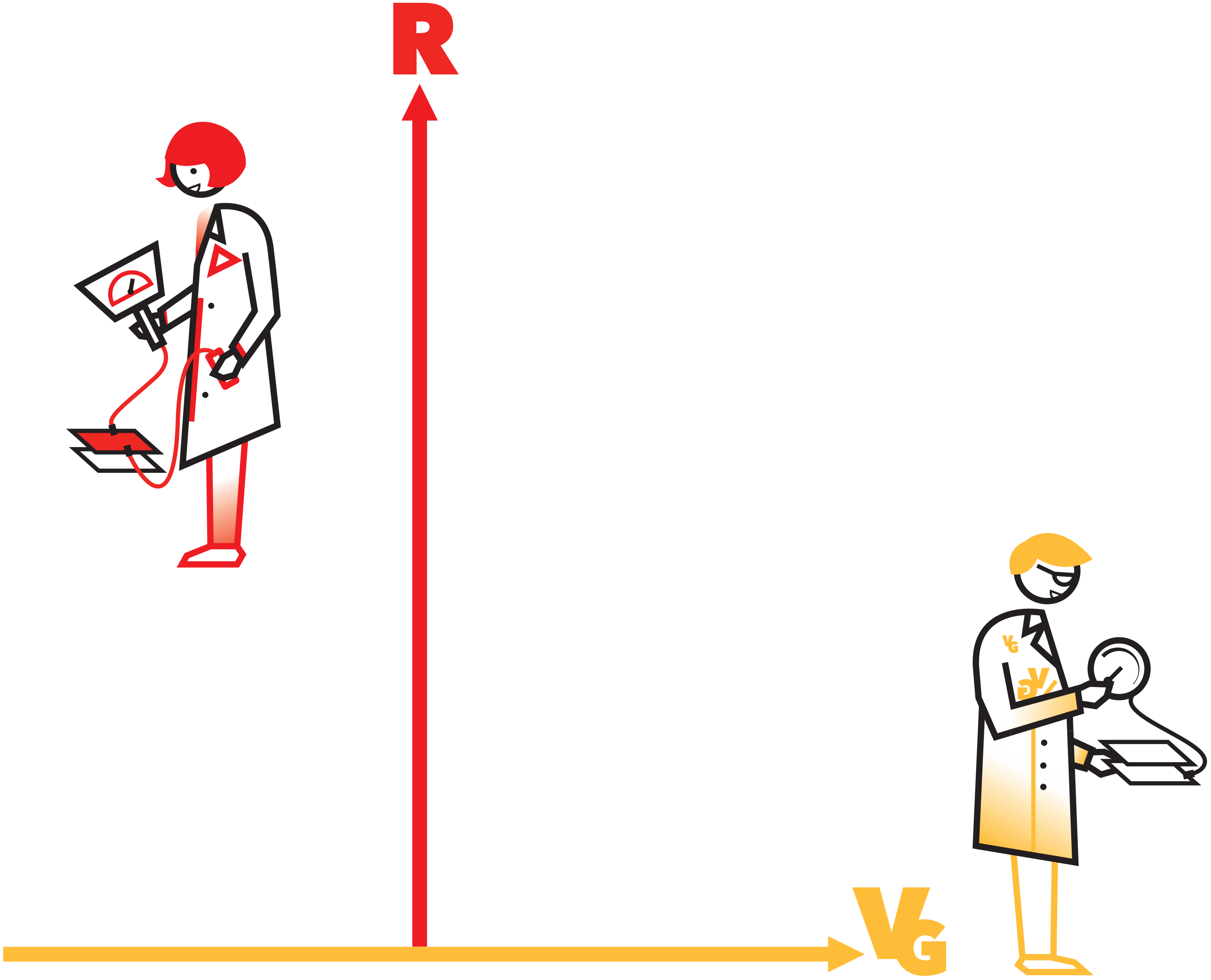
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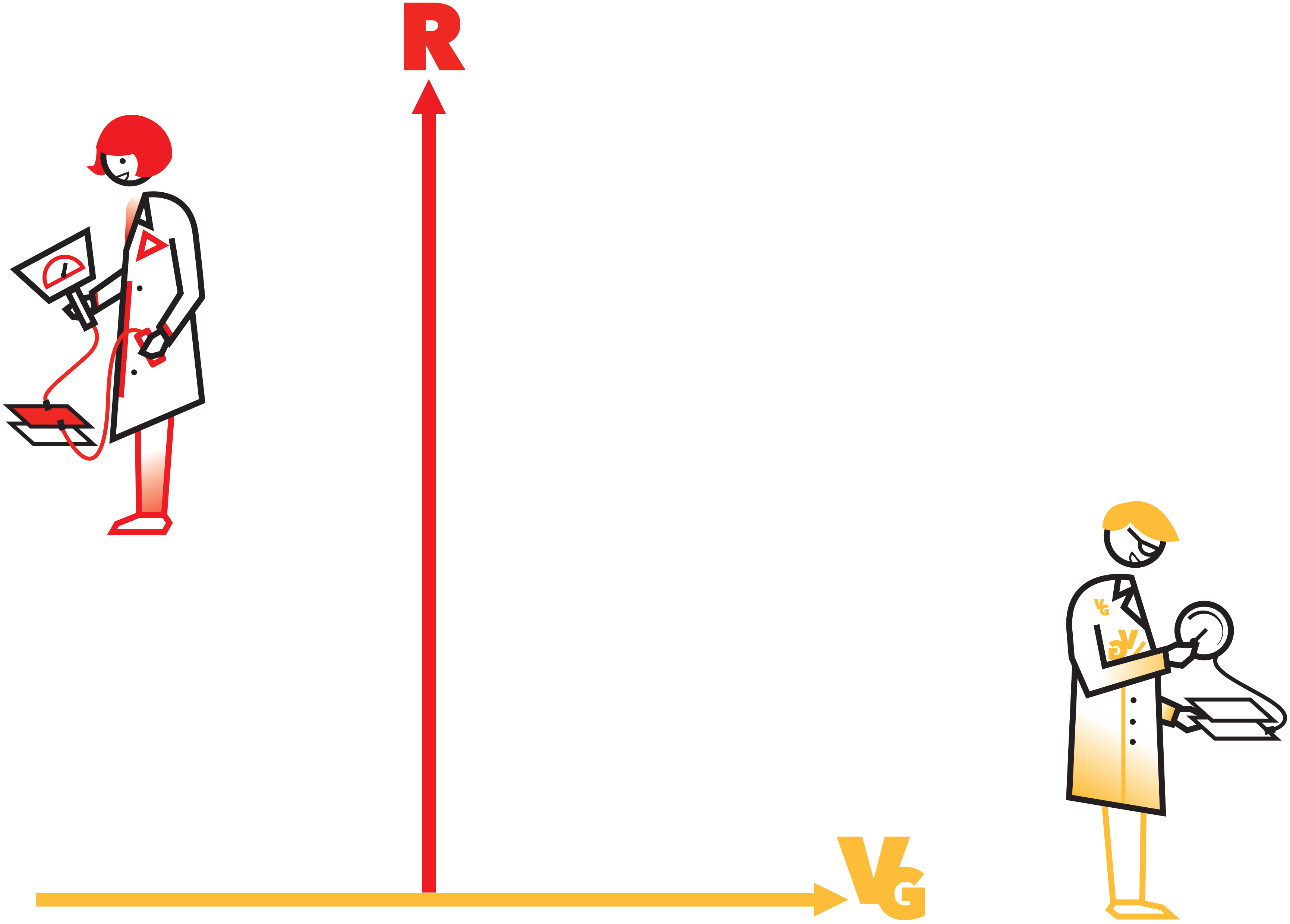
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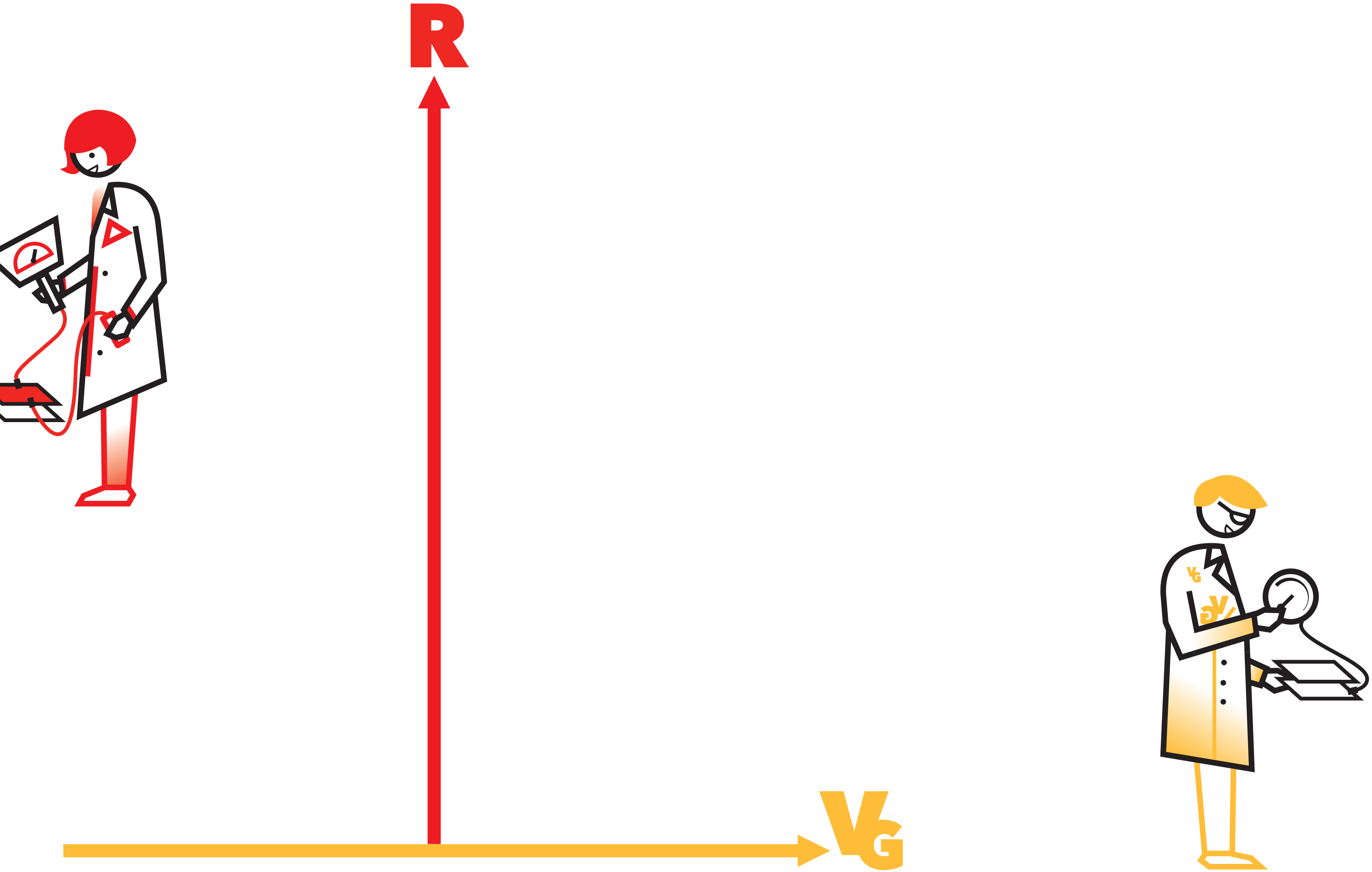
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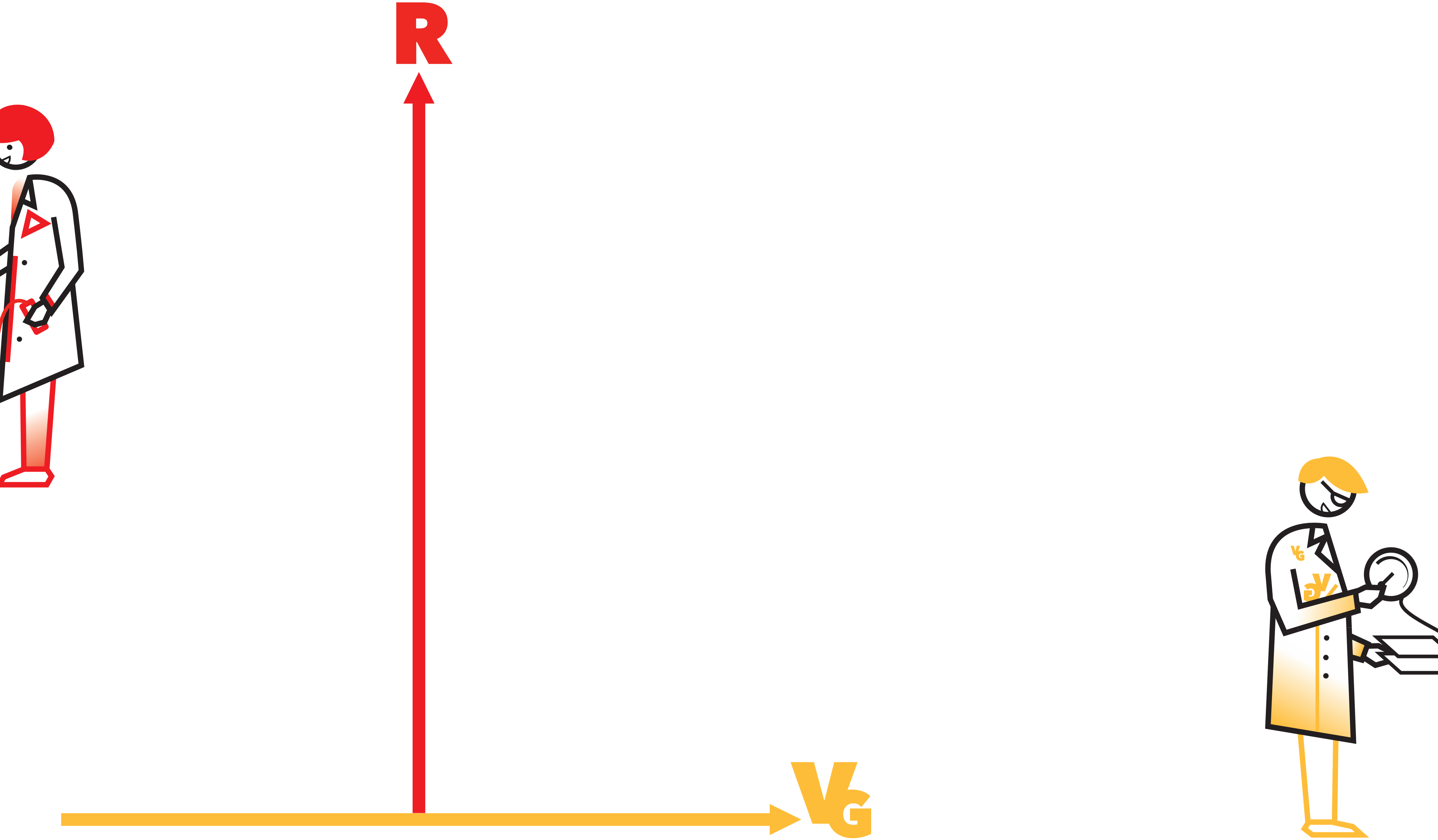
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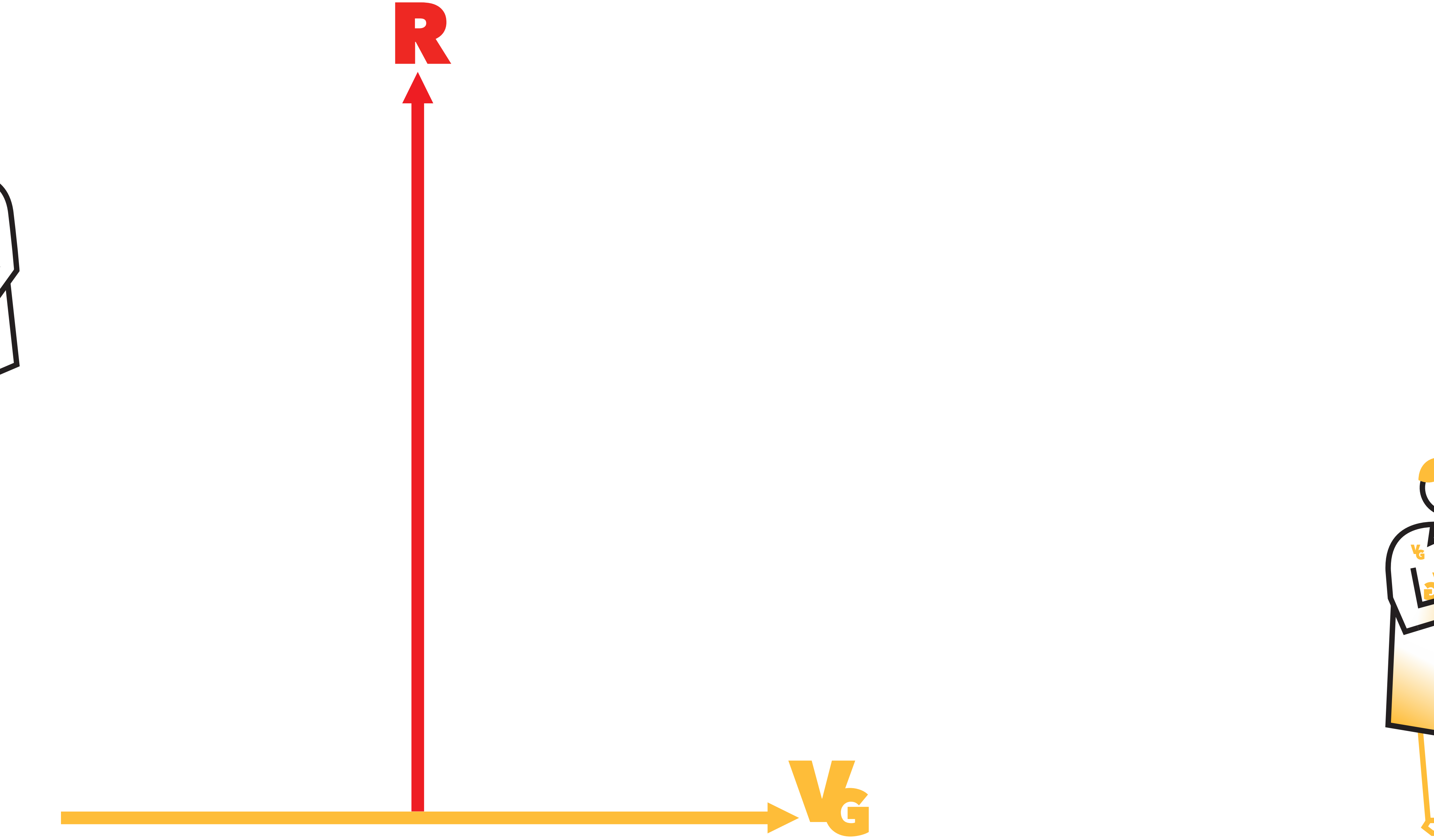
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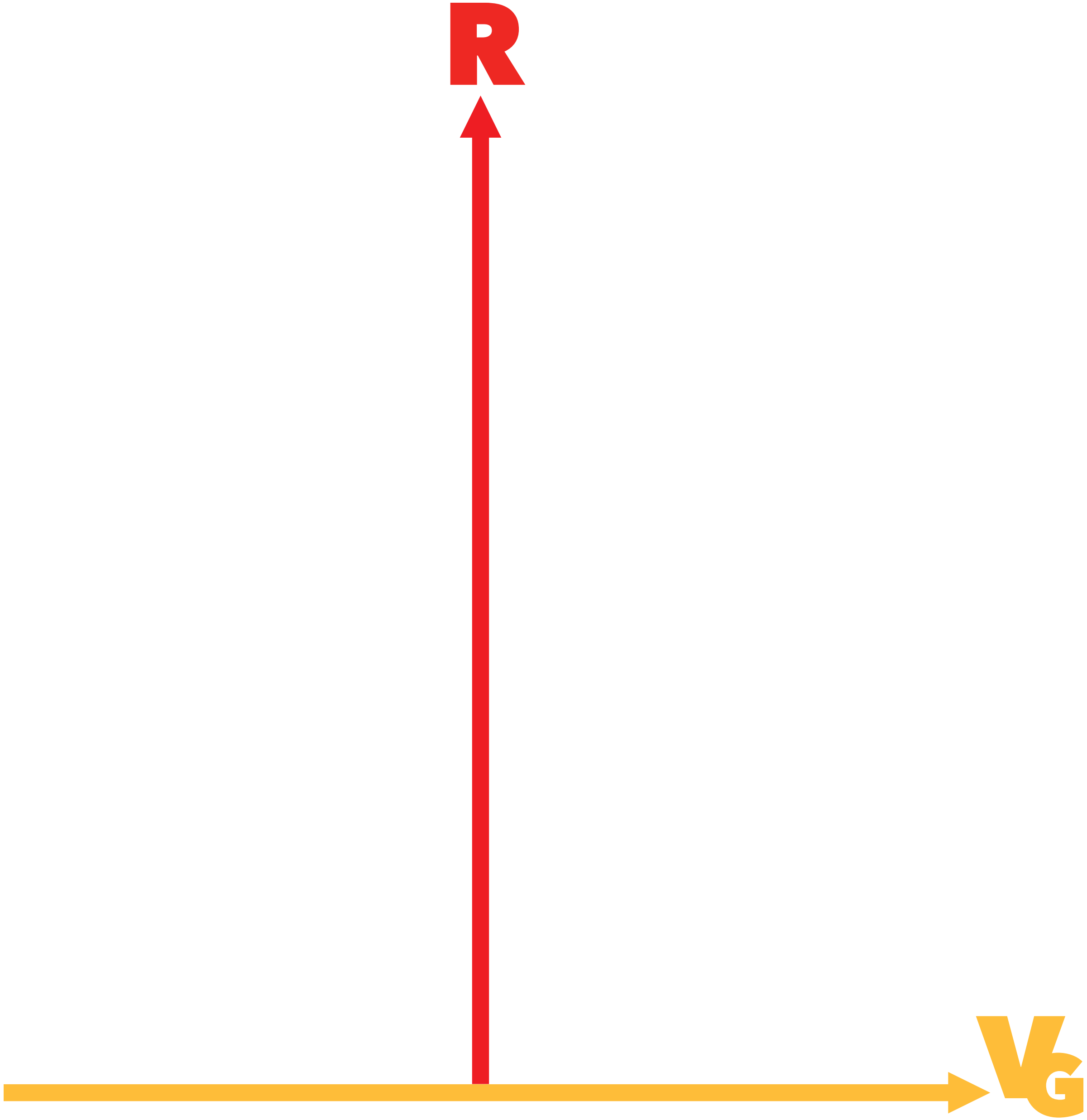
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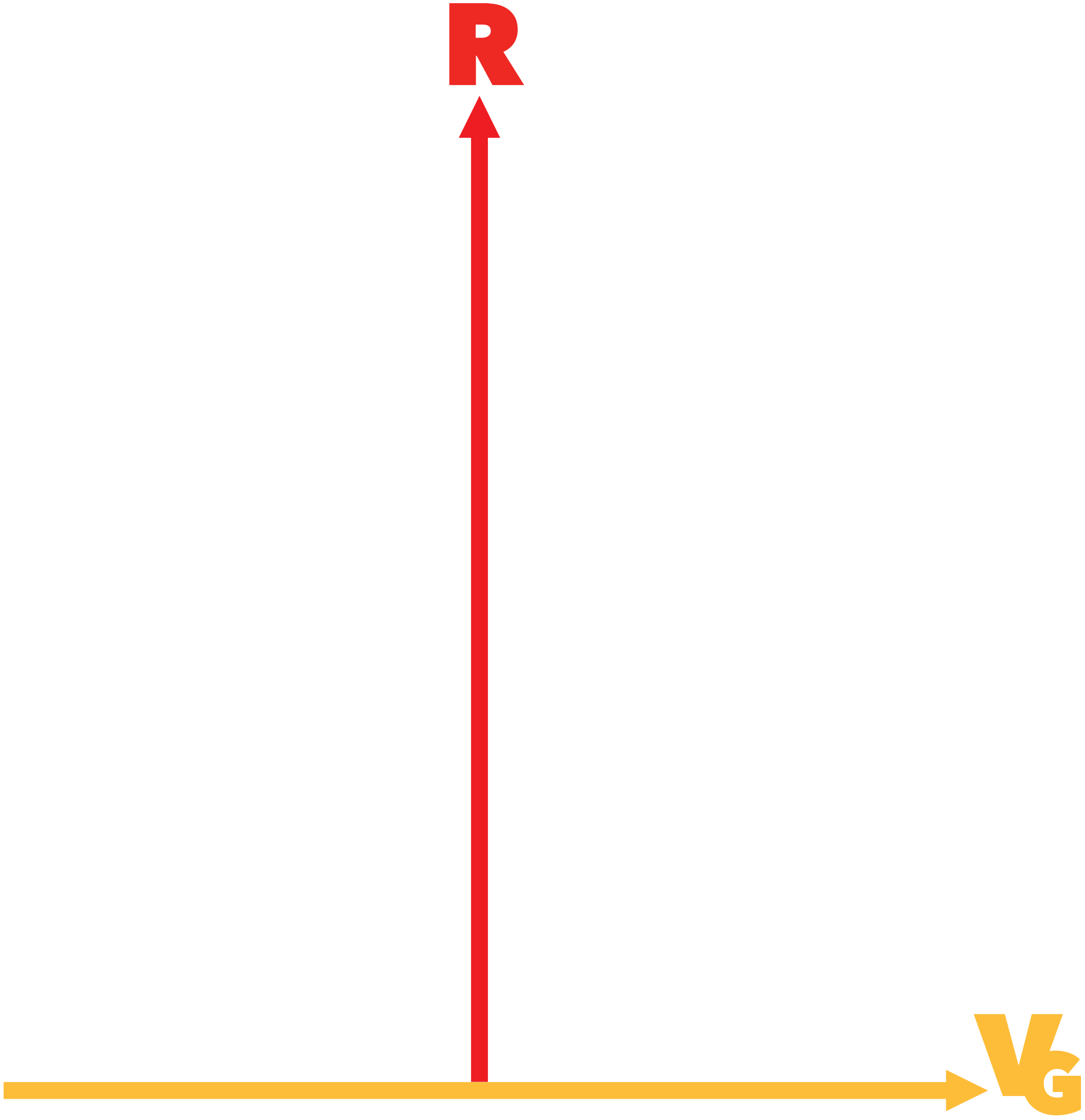
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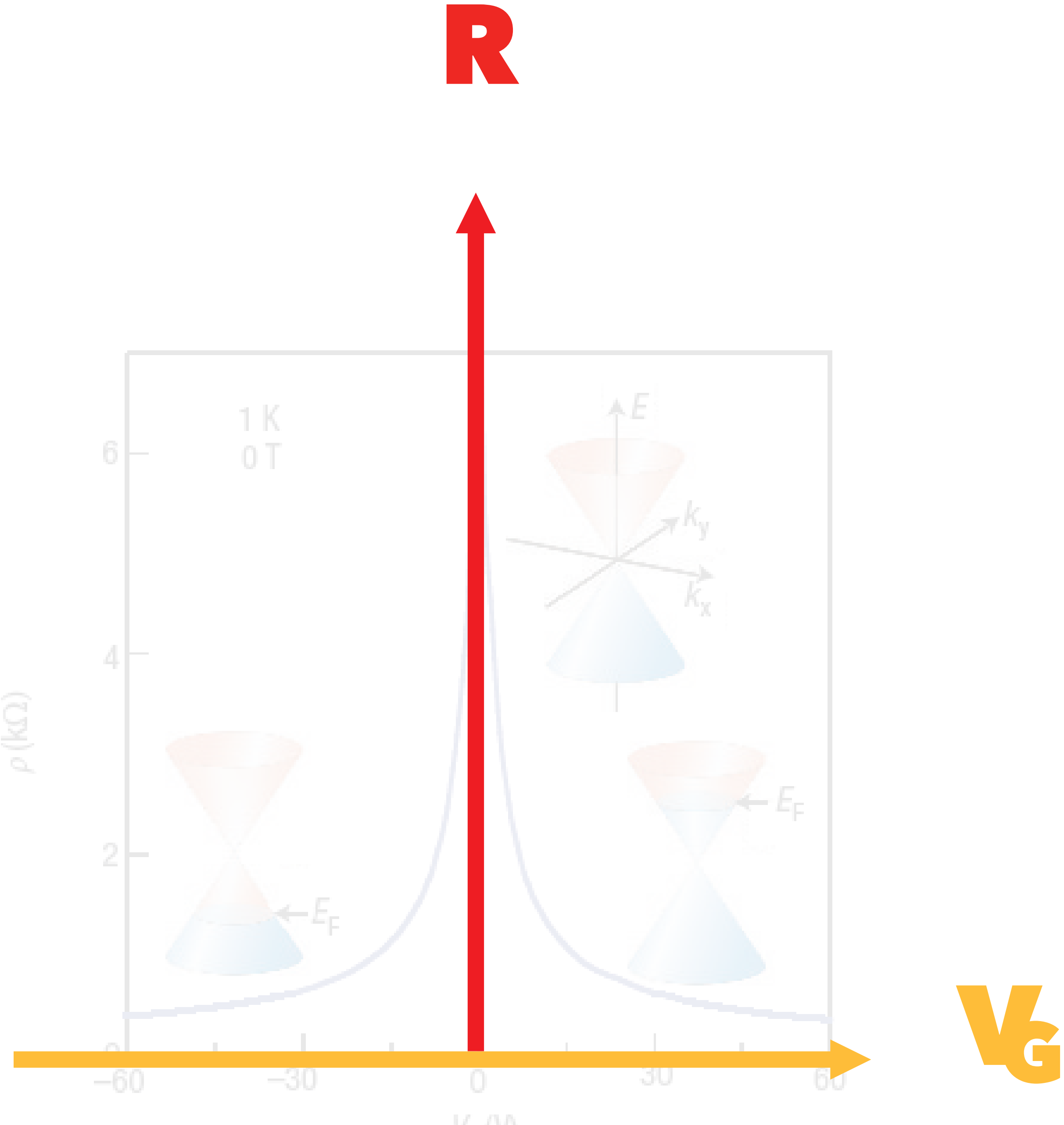
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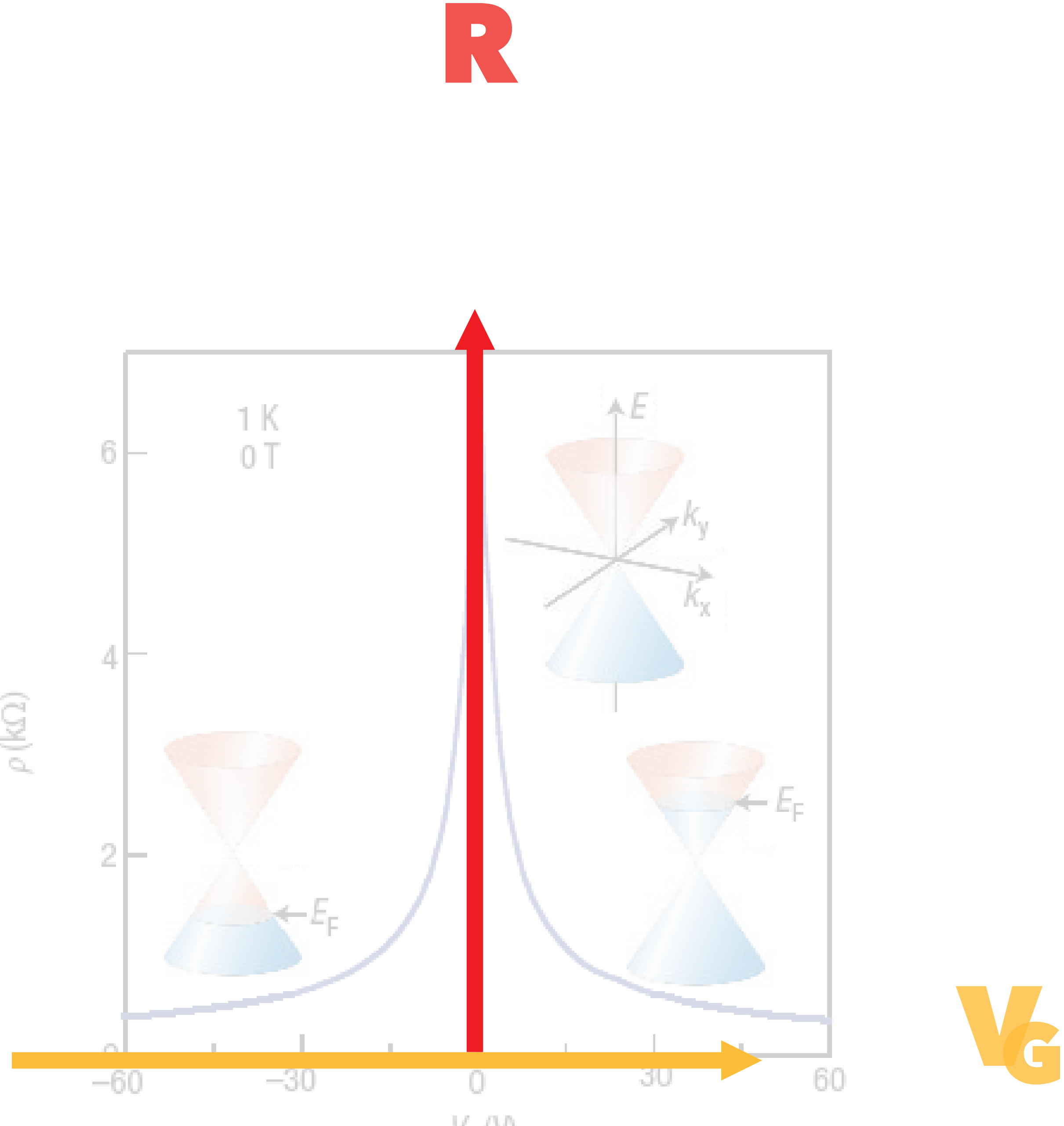
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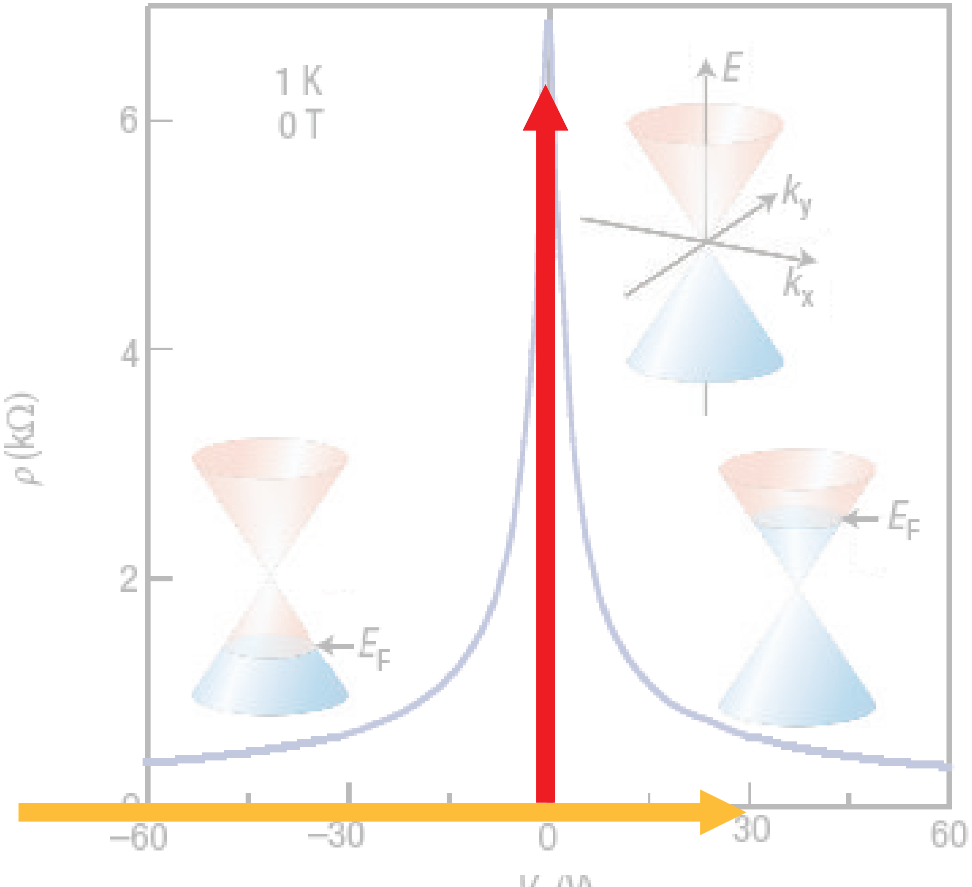

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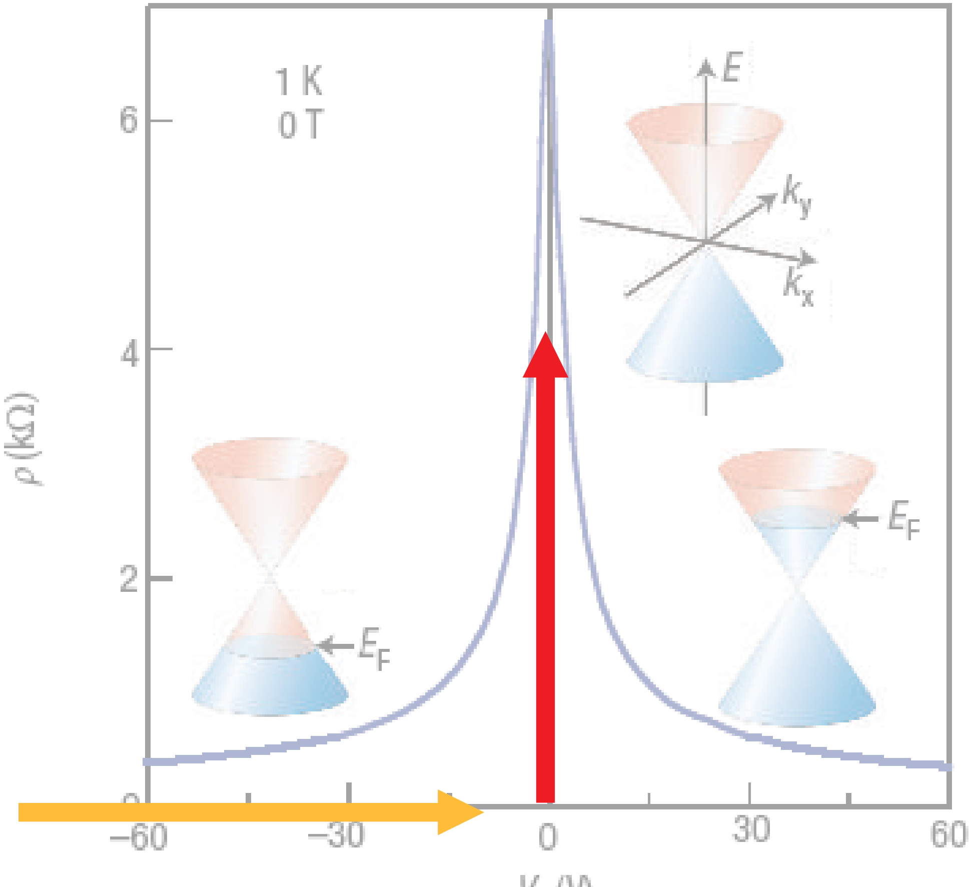

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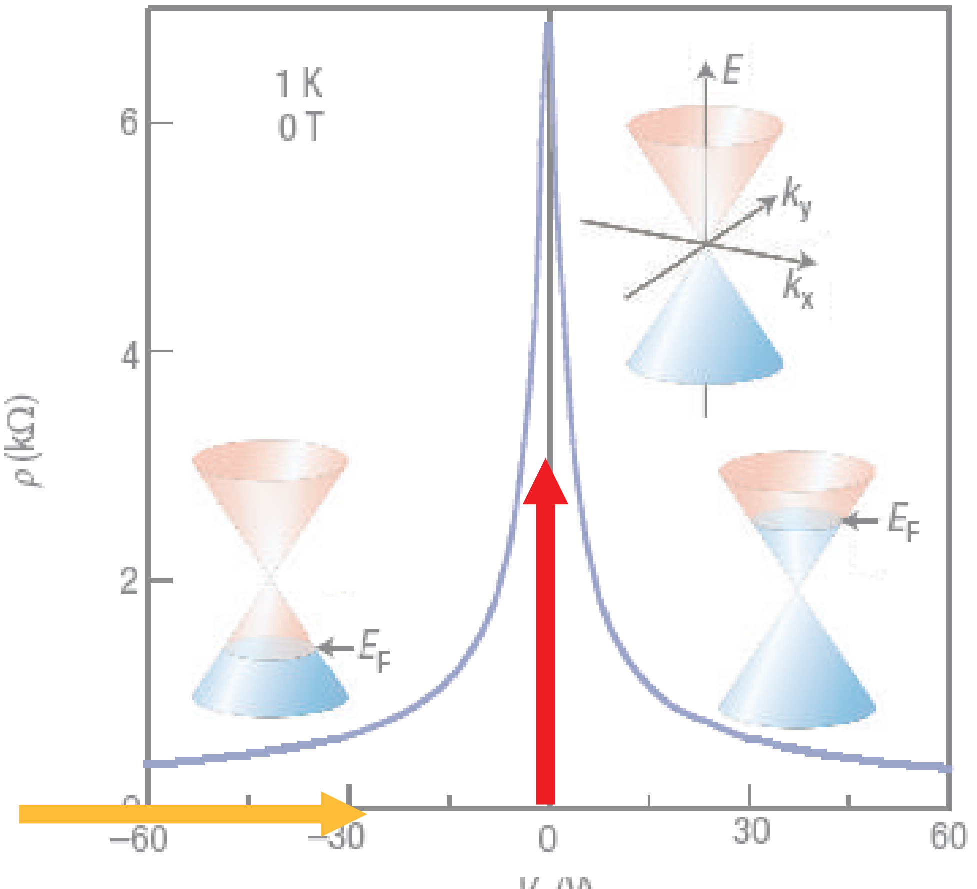

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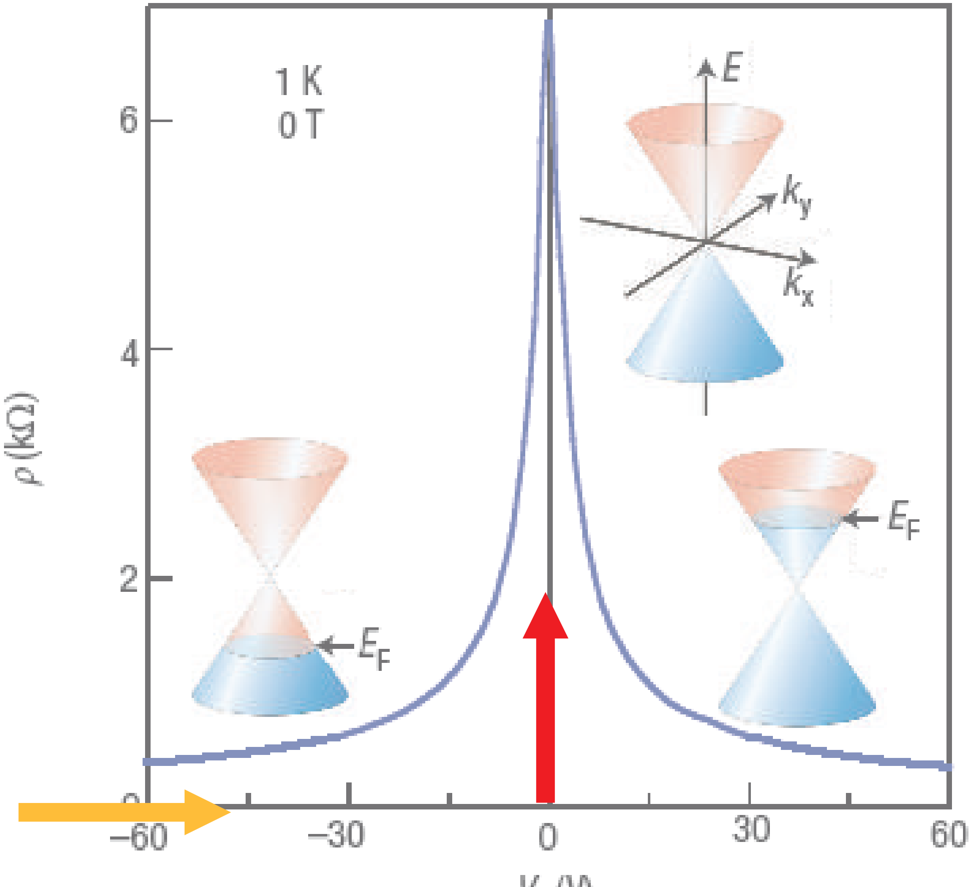

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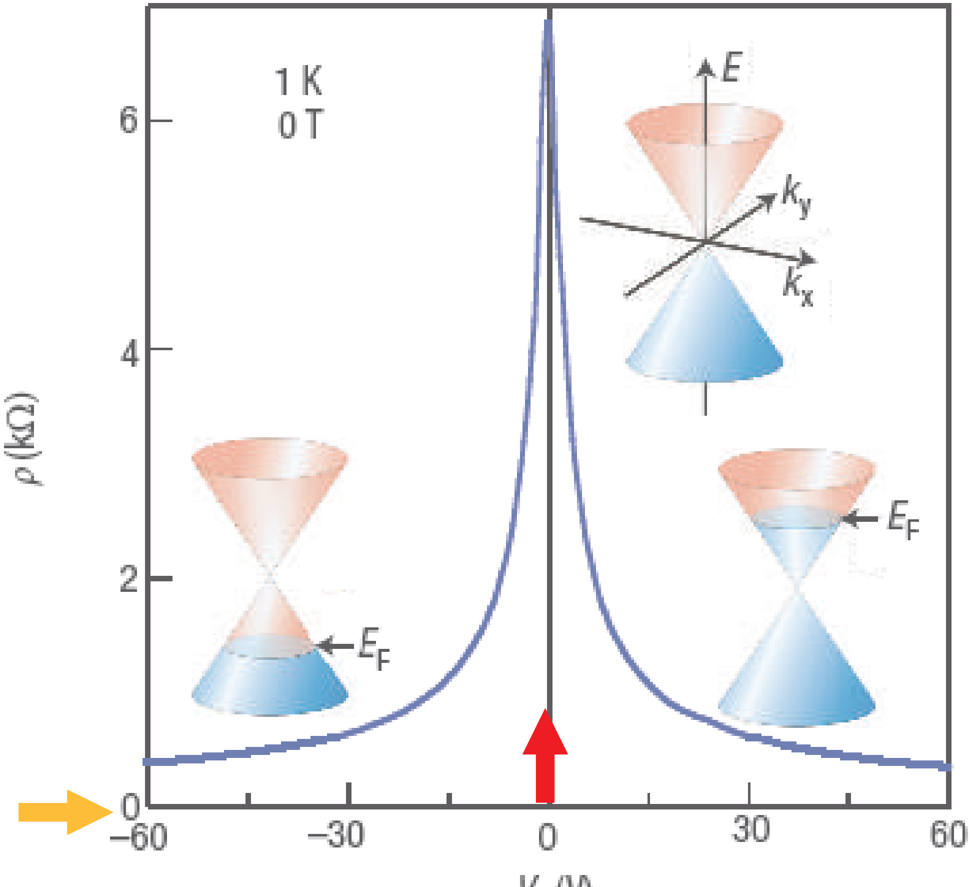

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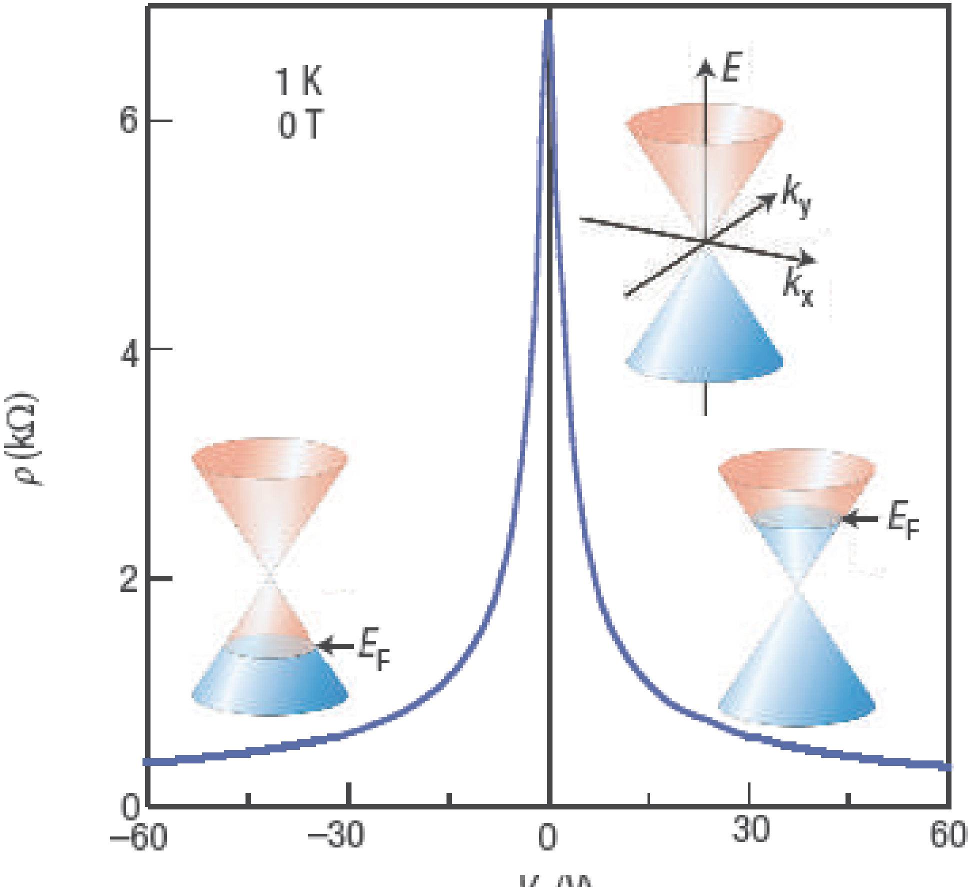

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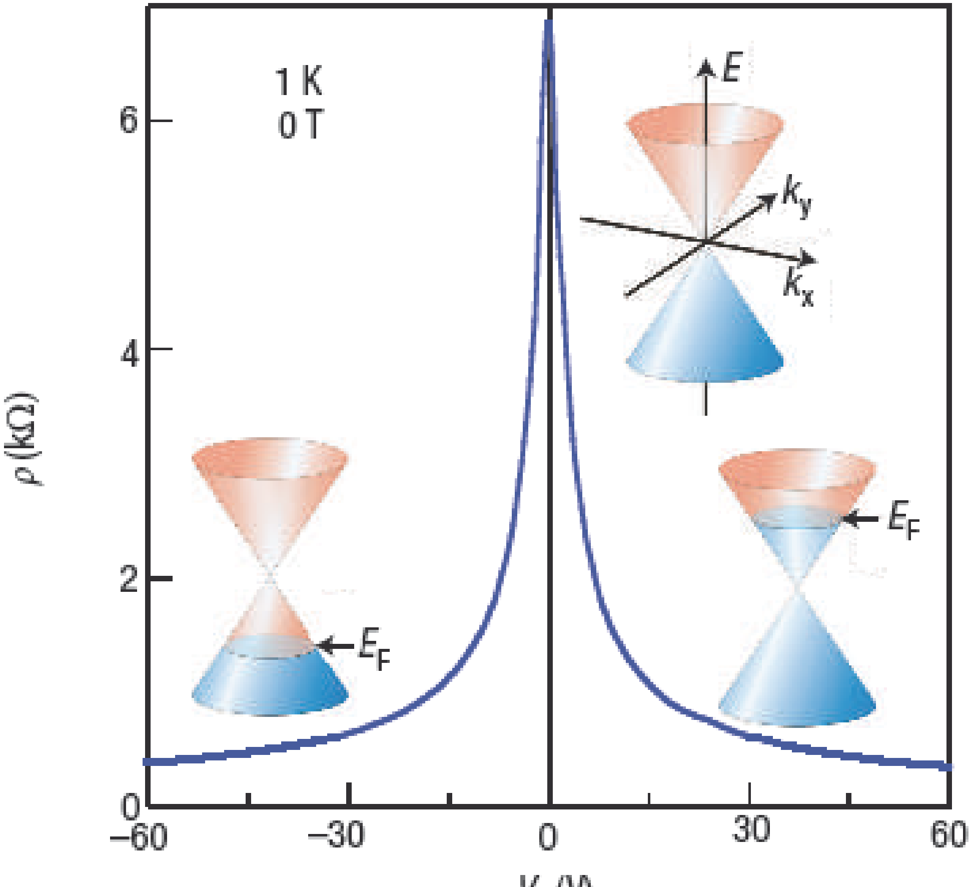
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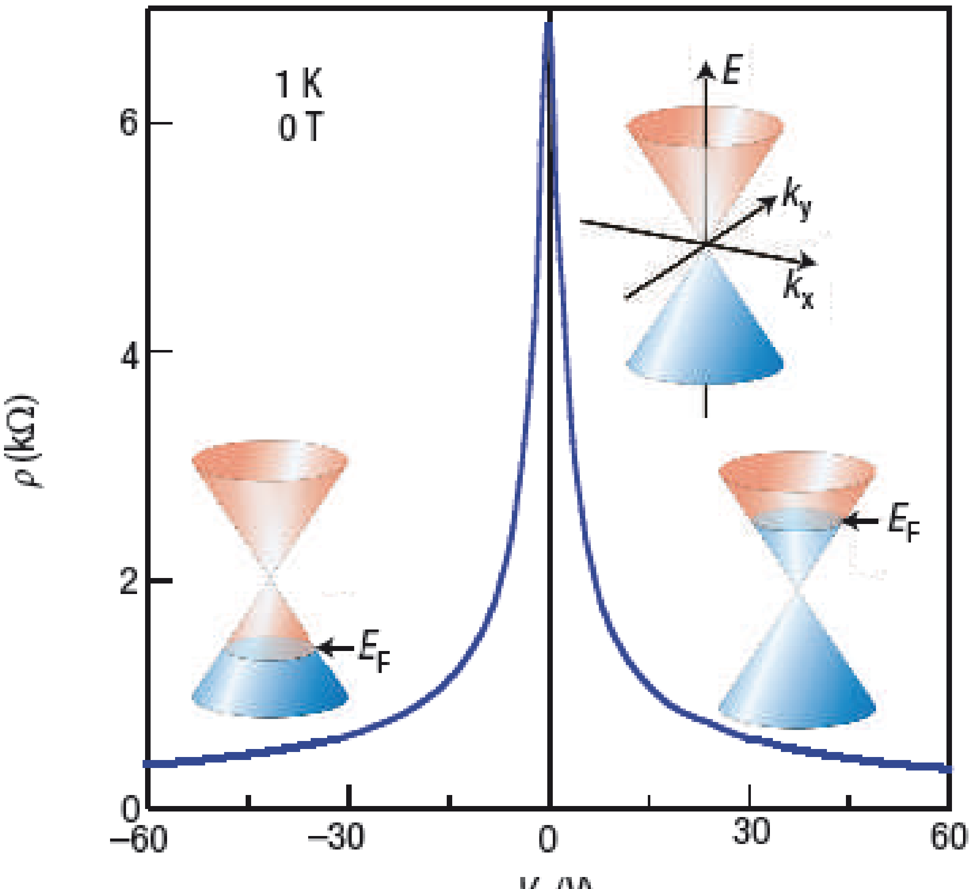
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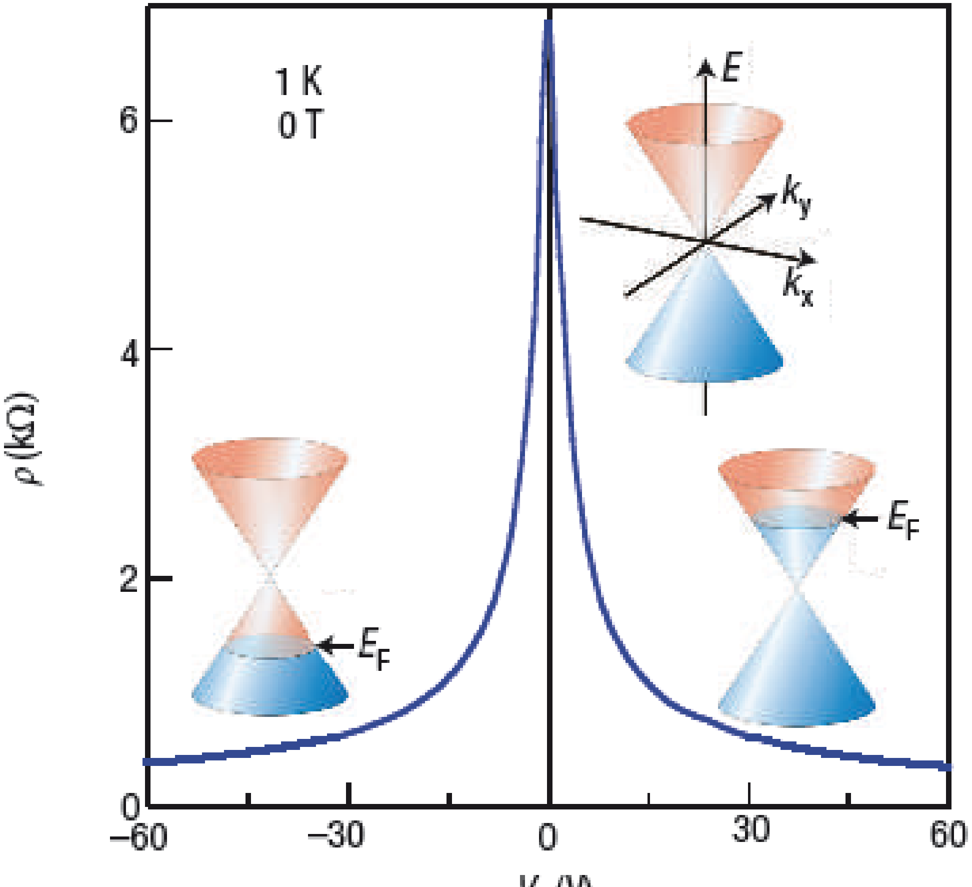
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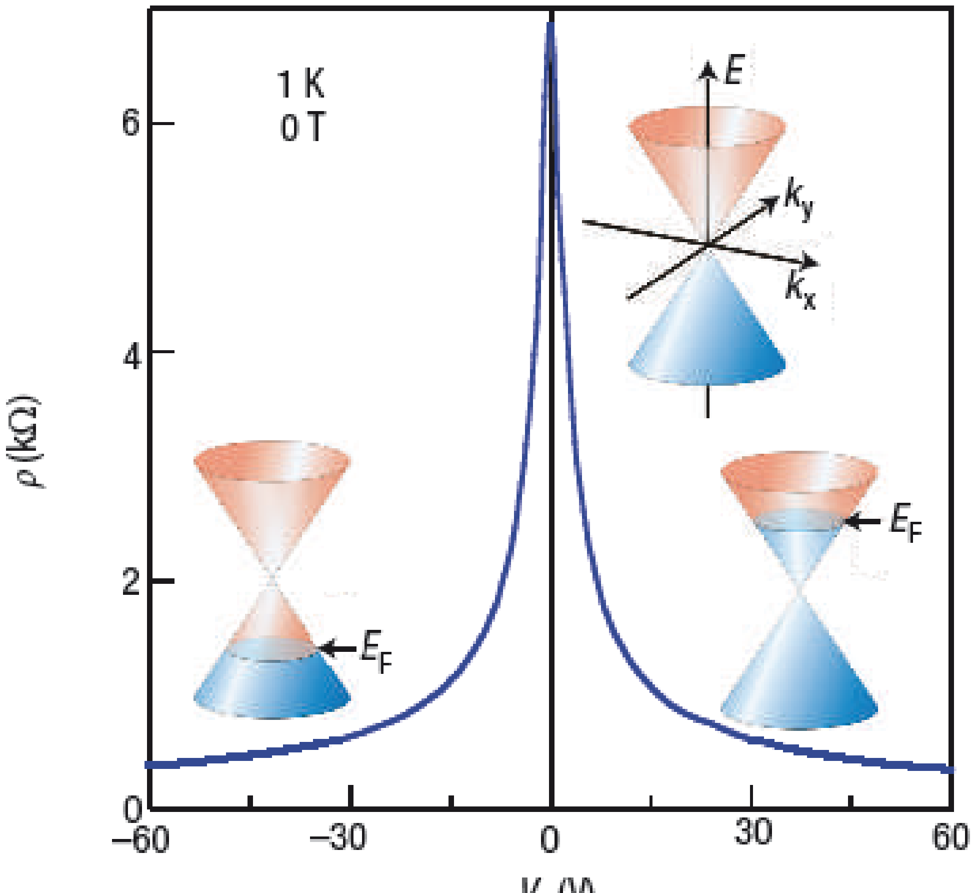
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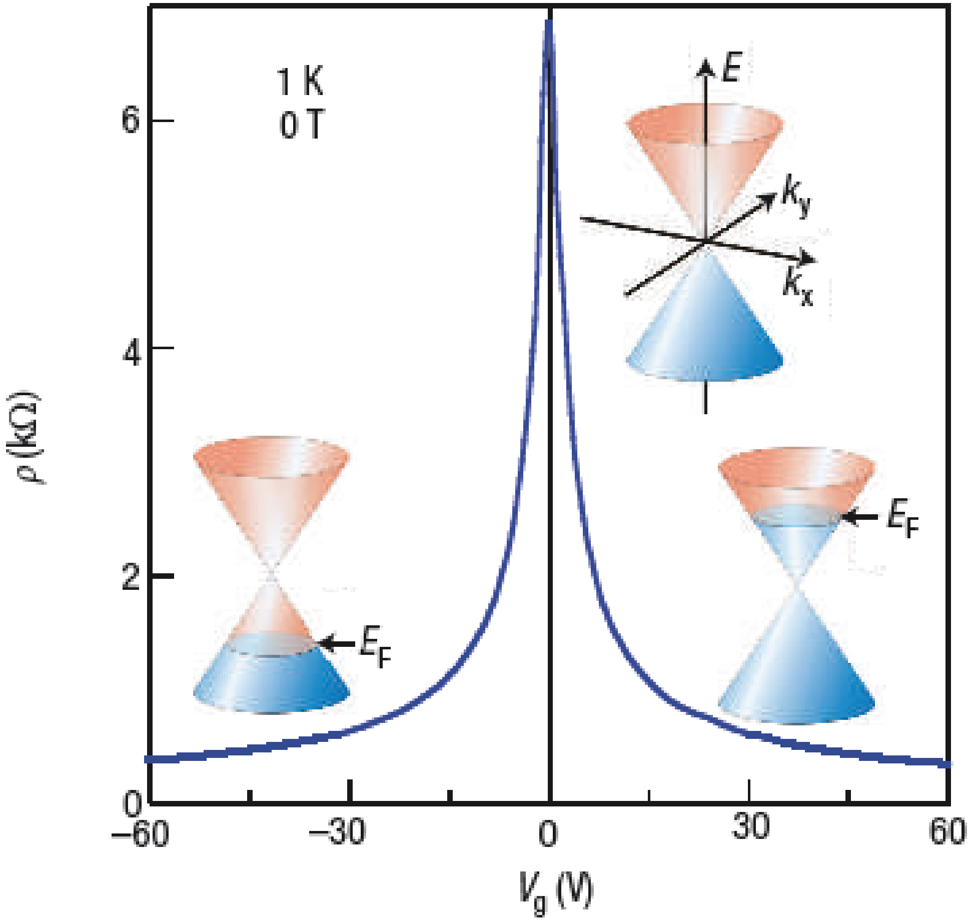
V_g (V)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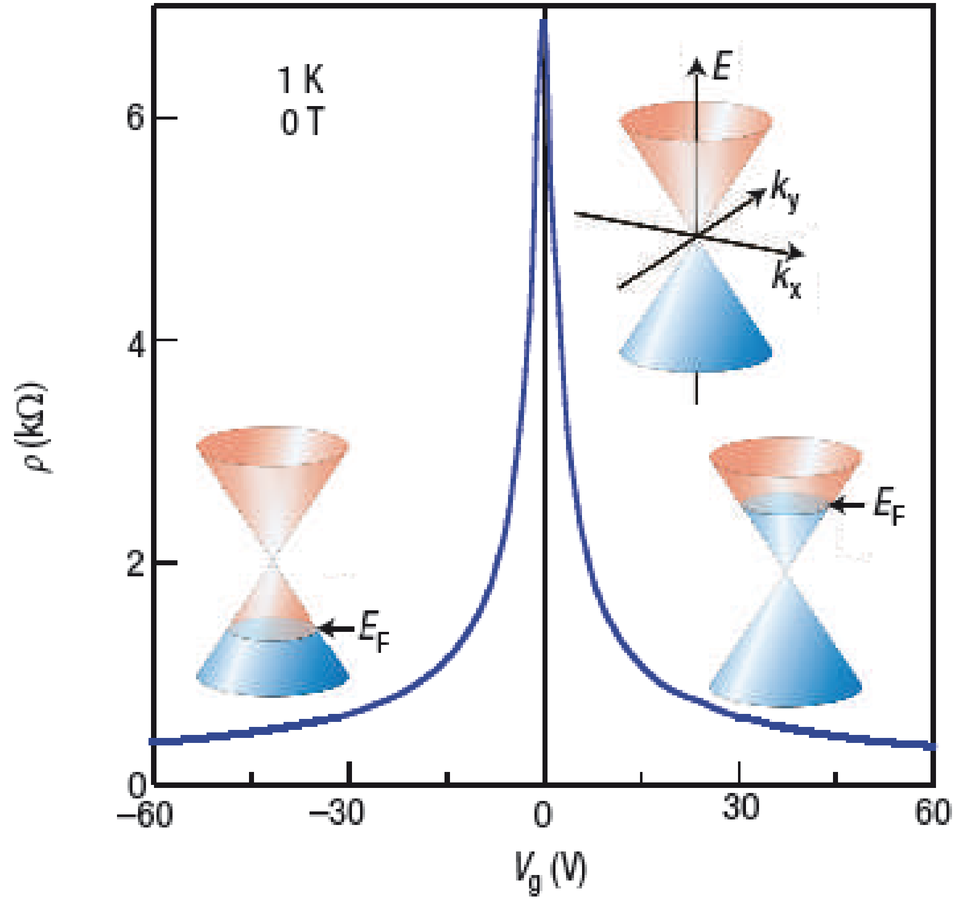
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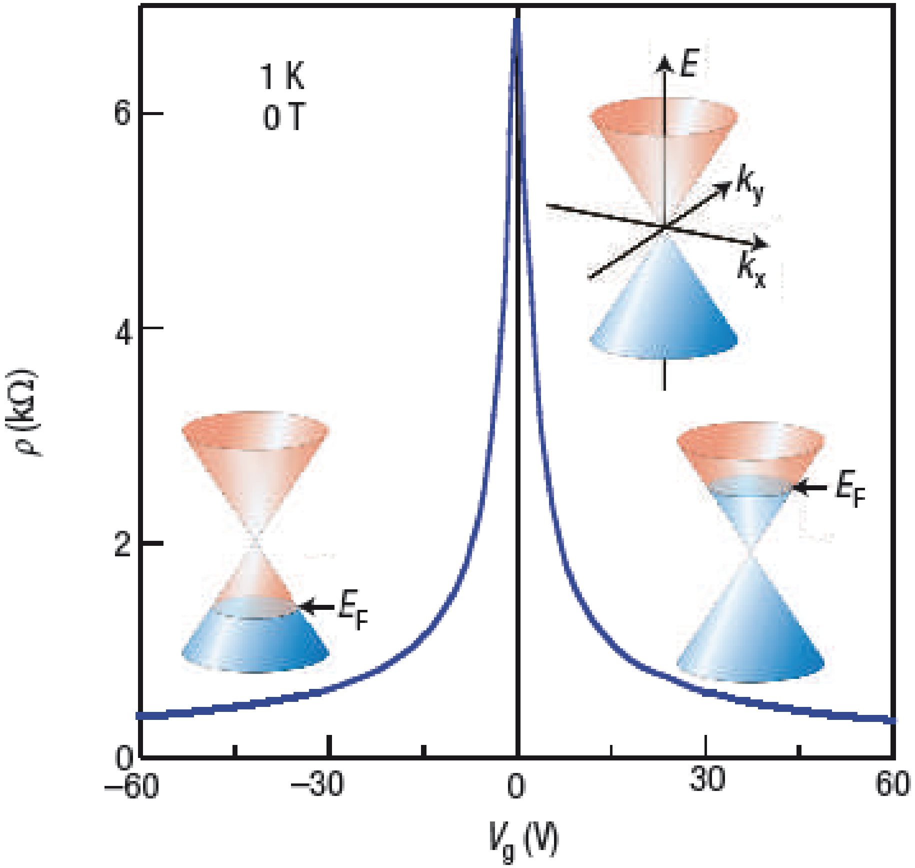
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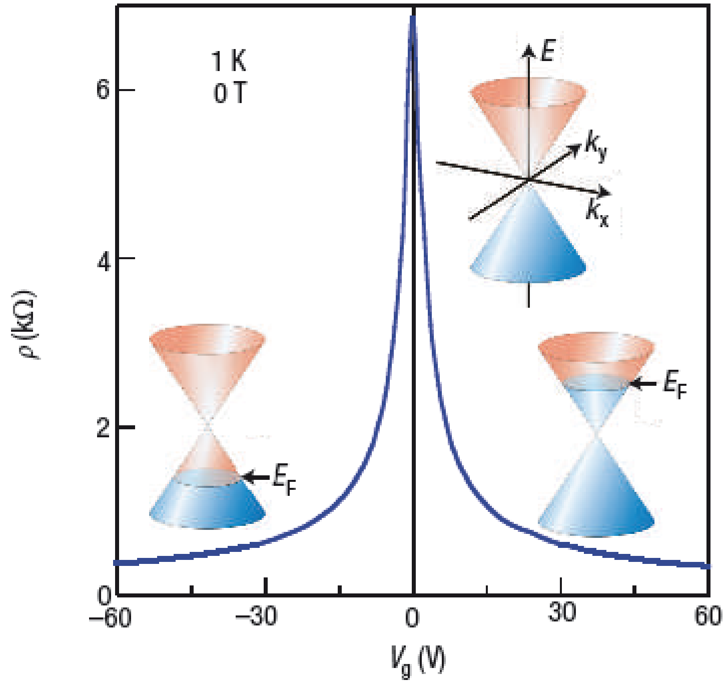
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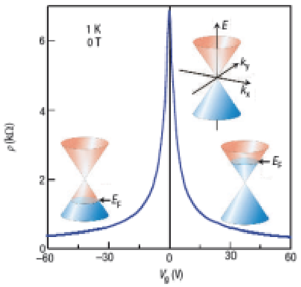

Figure 3 Ambipolar electric field effect in single-layer graphene. The insets show its conical low-energy spectrum $E(k)$, indicating changes in the position of the Fermi energy E_F with changing gate voltage V_g. Positive (negative) V_g induce electrons (holes) in concentrations $n = \alpha V_g$ where the coefficient $\alpha \approx 7.2\times10^{10}$ cm^{-2} V^{-1} for field-effect devices with a 300 nm SiO$_2$ layer used as a dielectric[7–9]. The rapid decrease in resistivity ρ on adding charge carriers indicates their high mobility (in this case, $\mu \approx 5{,}000$ cm^2 V^{-1} s^{-1} and does not noticeably change with increasing temperature to 300 K).

Although there is nothing particularly relativistic about electrons moving around carbon atoms, their interaction with the periodic potential of graphene's honeycomb lattice gives rise to new quasiparticles that at low energies E are accurately described by the (2+1)-dimensional Dirac equation with an effective speed of light $v_F \approx 10^6$ m^{-1}s^{-1}. These quasiparticles, called massless Dirac fermions, can be seen as electrons that have lost their rest mass m_0 or as neutrinos that acquired the electron charge e. The relativistic-like description of electron waves on honeycomb lattices has been known theoretically for many years, never failing to attract attention, and the experimental discovery of graphene now provides a way to probe quantum electrodynamics (QED) phenomena by measuring graphene's electronic properties.

QED IN A PENCIL TRACE

From the point of view of its electronic properties, graphene is a zero-gap semiconductor, in which low-E quasiparticles within each valley can formally be described by the Dirac-like hamiltonian

$$\hat{H} = \hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = \hbar v_F \boldsymbol{\sigma}\cdot\mathbf{k}\,, \qquad (1)$$

where $\mathbf{k}$ is the quasiparticle momentum, σ the 2D Pauli matrix and the k-independent Fermi velocity v_F plays the role of the speed of light. The Dirac equation is a direct consequence of graphene's crystal symmetry. Its honeycomb lattice is made up of two equivalent carbon sublattices A and B, and cosine-like energy bands associated with the sublattices intersect at zero E near the edges of the Brillouin zone, giving rise to conical sections of the energy spectrum for $|E| < 1$ eV (Fig. 3).

We emphasize that the linear spectrum $E = \hbar v_F k$ is not the only essential feature of the band structure. Indeed, electronic states near zero E (where the bands intersect) are composed of states belonging to the different sublattices, and their relative contributions in the make-up of quasiparticles have to be taken into account by, for example, using two-component wavefunctions (spinors). This requires an index to indicate sublattices A and B, which is similar to the spin index (up and down) in QED and, therefore, is referred to as pseudospin. Accordingly, in the formal description of graphene's quasiparticles by the Dirac-like hamiltonian above, σ refers to pseudospin rather than the real spin of electrons (the latter must be described by additional terms in the hamiltonian). Importantly, QED-specific phenomena are often inversely proportional to the speed of light c, and therefore enhanced in graphene by a factor $c/v_F \approx 300$. In particular, this means that pseudospin-related effects should generally dominate those due to the real spin.

By analogy with QED, one can also introduce a quantity called chirality[6] that is formally a projection of σ on the direction of motion $\mathbf{k}$ and is positive (negative) for electrons (holes). In essence, chirality in graphene signifies the fact that k electron and $-k$ hole states are intricately connected because they originate from the same carbon sublattices. The concepts of chirality and pseudospin are important because many electronic processes in graphene can be understood as due to conservation of these quantities[6,43–48].

It is interesting to note that in some narrow-gap 3D semiconductors, the gap can be closed by compositional changes or by applying high pressure. Generally, zero gap does not necessitate Dirac fermions (that imply conjugated electron and hole states), but in some cases they might appear[5]. The difficulties of tuning the gap to zero, while keeping carrier mobilities high, the lack of possibility to control electronic properties of 3D materials by the electric field effect and, generally, less pronounced quantum effects in 3D limited studies of such semiconductors mostly to measuring the concentration dependence of their effective masses m (for a review, see ref. 49). It is tempting to have a fresh look at zero-gap bulk semiconductors, especially because Dirac fermions have recently been reported even in such a well-studied (small-overlap) 3D material as graphite[50,51].

CHIRAL QUANTUM HALL EFFECTS

At this early stage, the main experimental efforts have been focused on the electronic properties of graphene, trying to understand the consequences of its QED-like spectrum. Among the most spectacular phenomena reported so far, there are two new ('chiral') quantum Hall effects (QHEs), minimum quantum conductivity in the limit of vanishing concentrations of charge carriers and strong suppression of quantum interference effects.

Figure 4 shows three types of QHE behaviour observed in graphene. The first one is a relativistic analogue of the integer QHE and characteristic of single-layer graphene[9,10]. It shows up as an uninterrupted ladder of equidistant steps in the Hall conductivity σ_{xy} which persists through the neutrality (Dirac) point, where charge carriers change from electrons to holes (Fig. 4a). The sequence is shifted with respect to the standard QHE sequence by ½, so that $\sigma_{xy} = \pm 4e^2/h\ (N + ½)$ where N is the Landau level (LL) index and factor 4 appears due to double valley and double spin degeneracy. This QHE has been dubbed 'half-integer' to reflect both the shift and the fact that, although it is not a new fractional QHE, it is not the standard integer QHE either. The unusual sequence is now well understood as arising from the QED-like quantization of graphene's electronic spectrum in magnetic field B, which is described[45,52–54] by $E_N = \pm v_F\sqrt{2e\hbar BN}$ where ± refers to electrons and holes. The existence of a quantized level at zero E, which is shared by electrons and holes (Fig. 4c), is essentially everything one needs to know to explain the anomalous QHE sequence[52–56]. An alternative explanation for the half-integer QHE is to invoke the coupling between pseudospin and orbital motion, which gives rise to a geometrical phase of π accumulated along cyclotron trajectories, which is often referred to as Berry's

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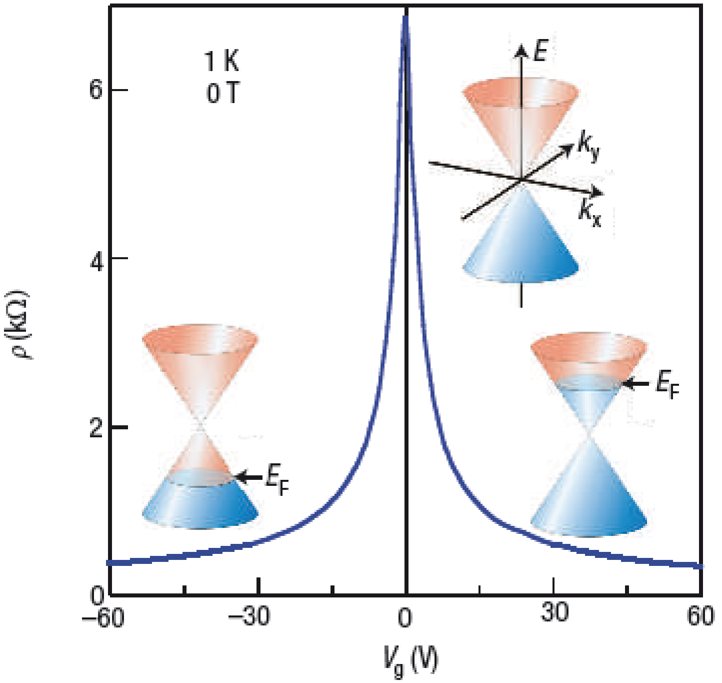

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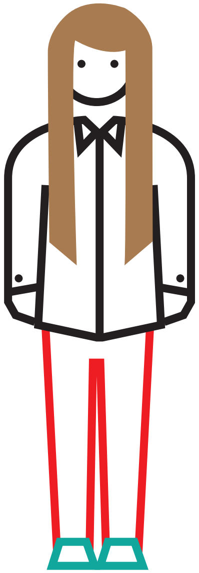

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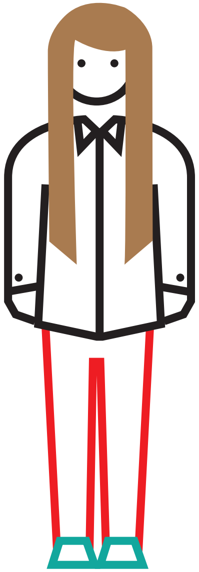

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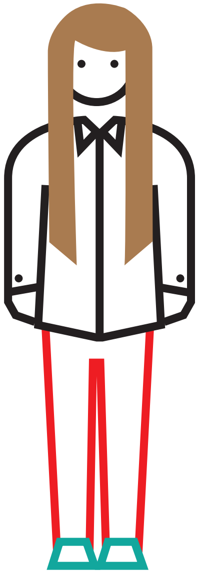

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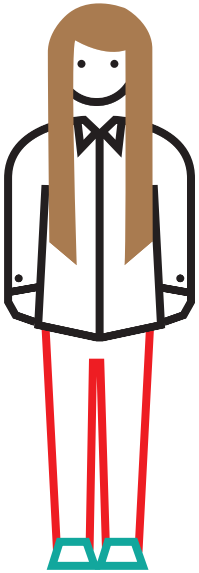

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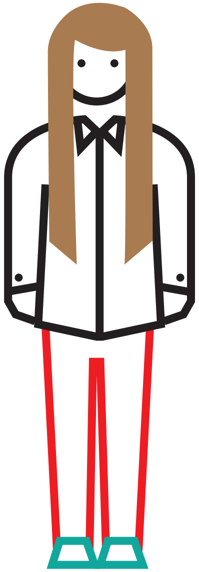

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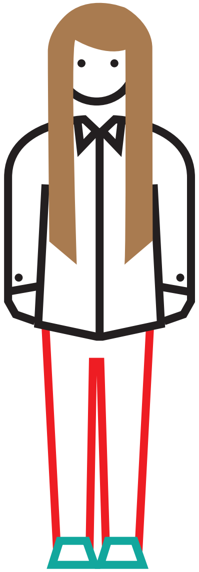

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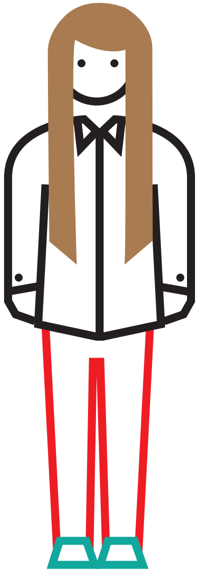

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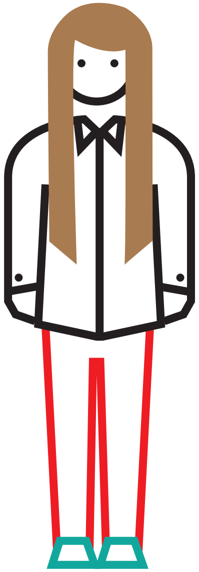

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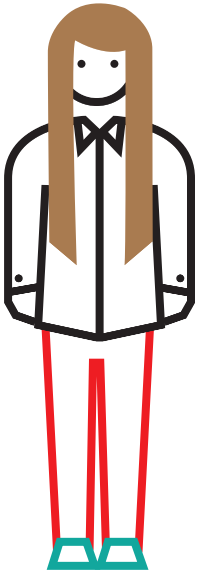

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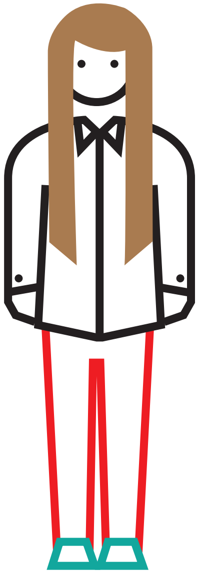

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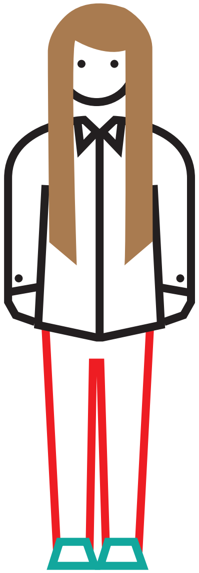

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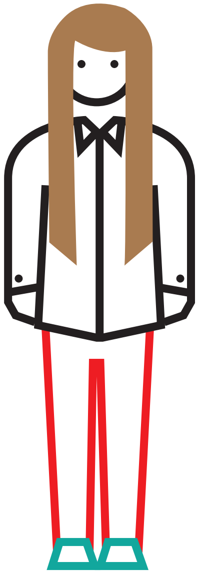

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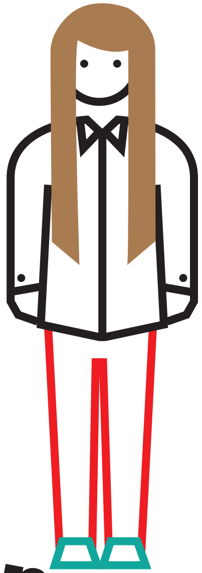

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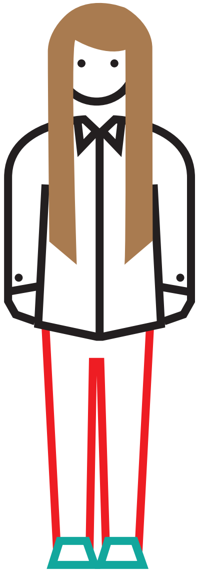

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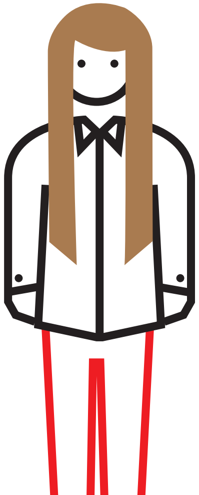

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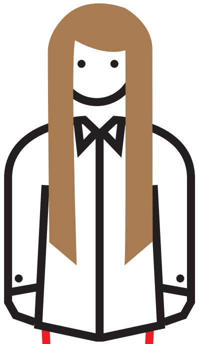

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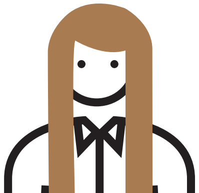

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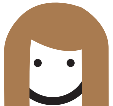

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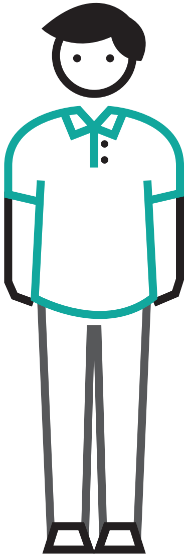

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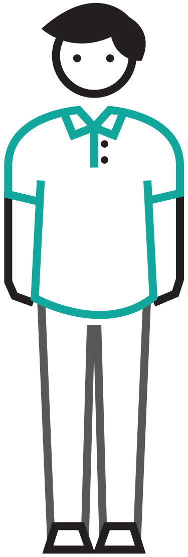

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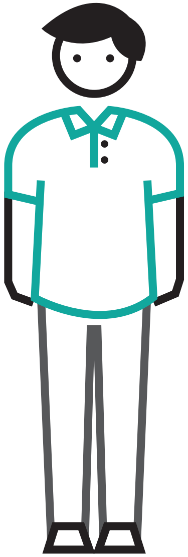

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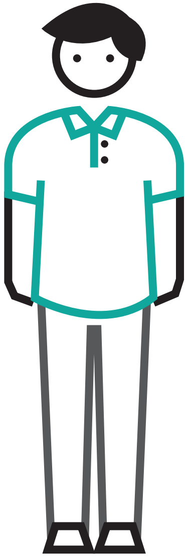

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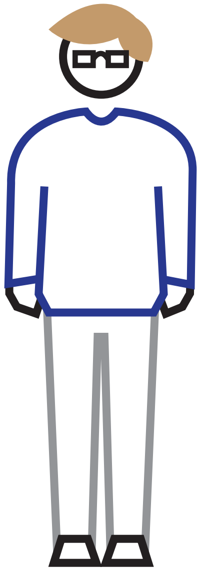

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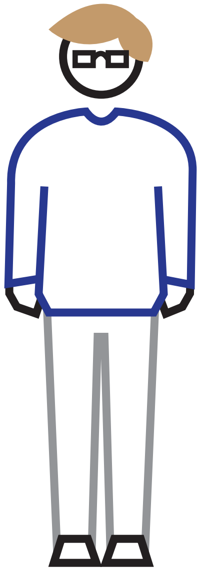

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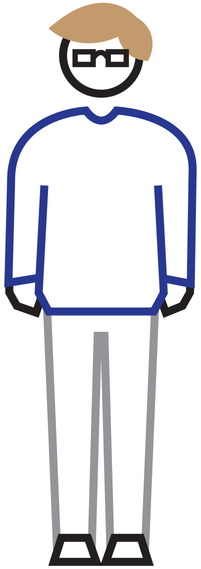

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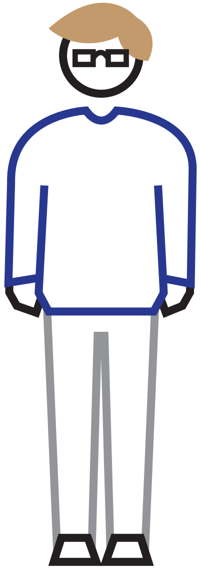

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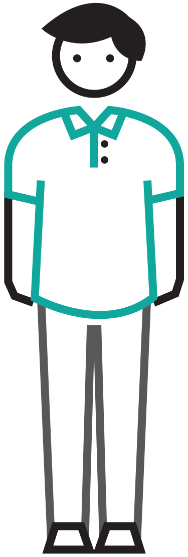

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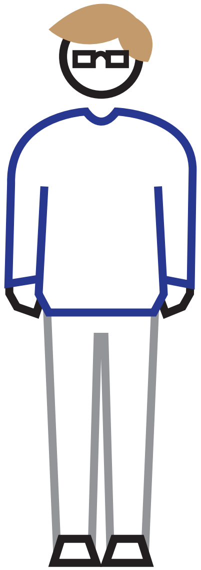

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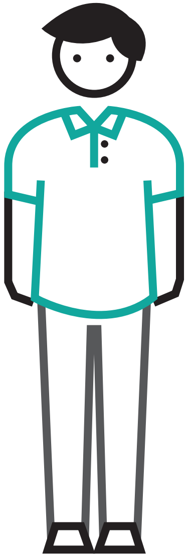

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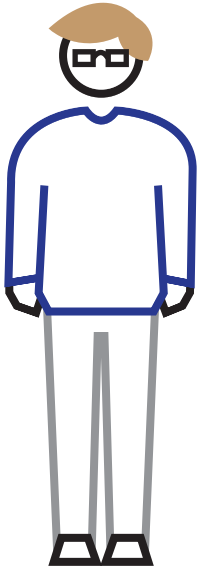

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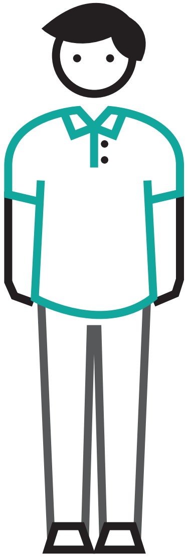

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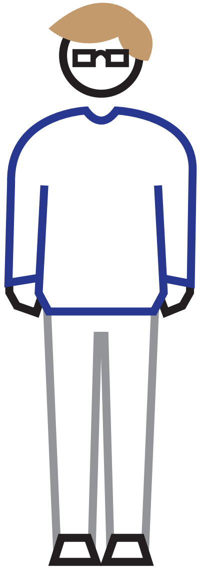

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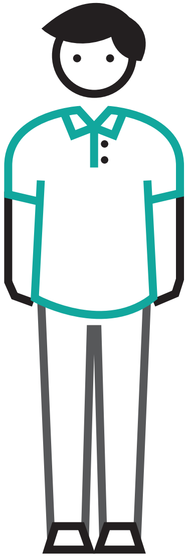

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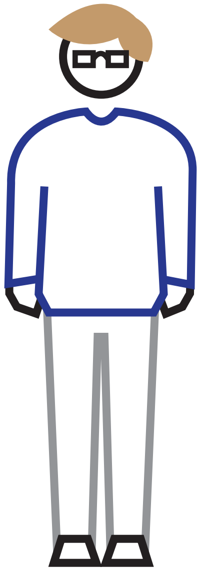

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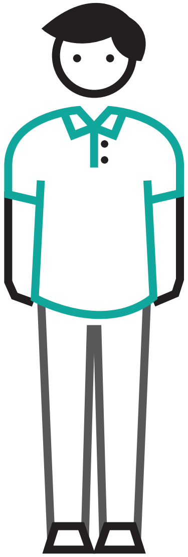

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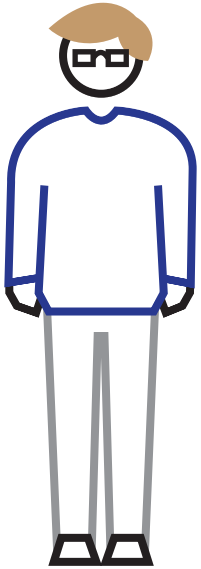

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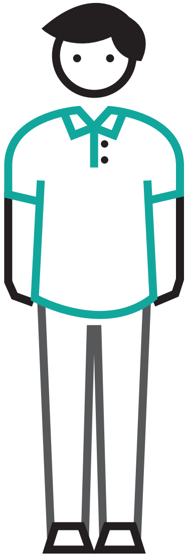

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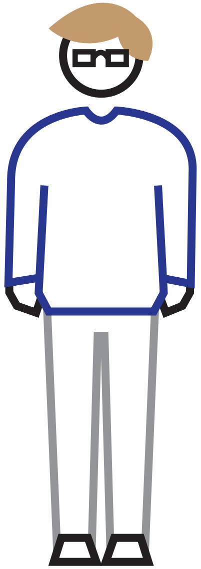

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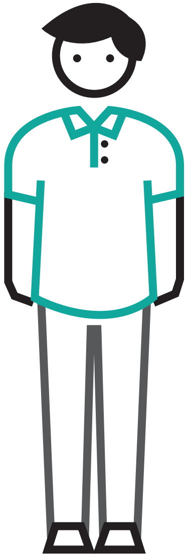

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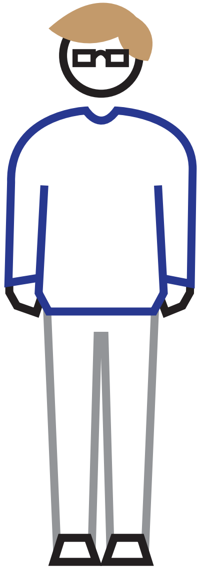

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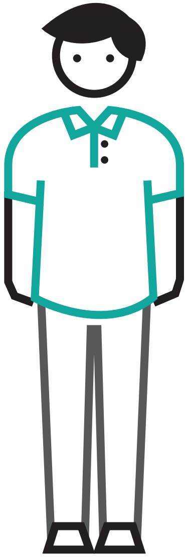

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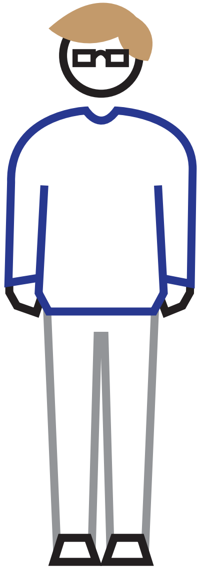

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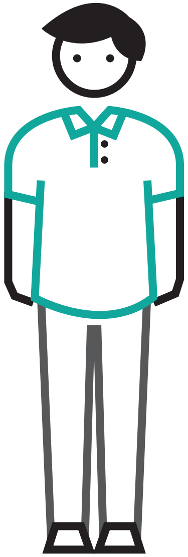

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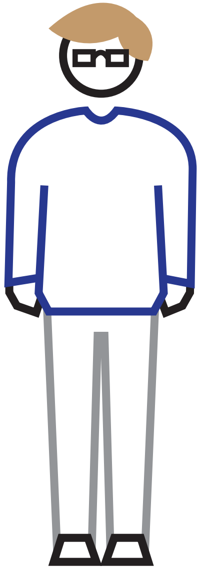

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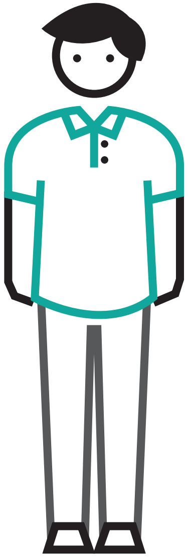

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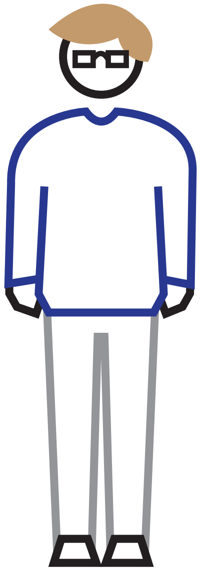

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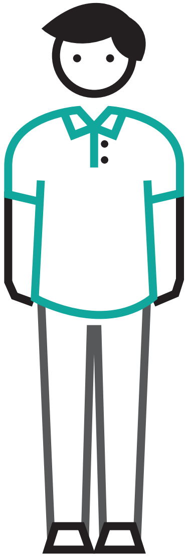

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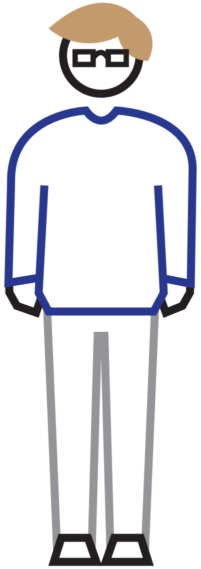

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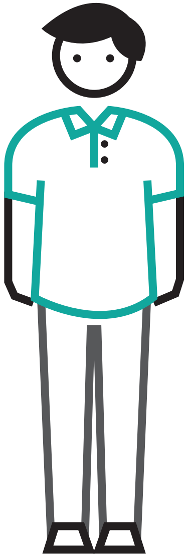

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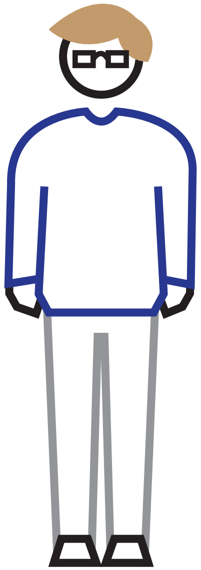

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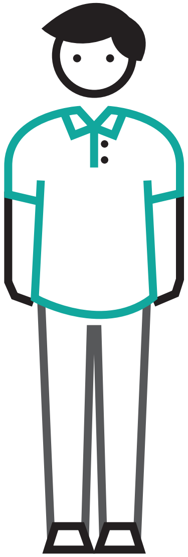

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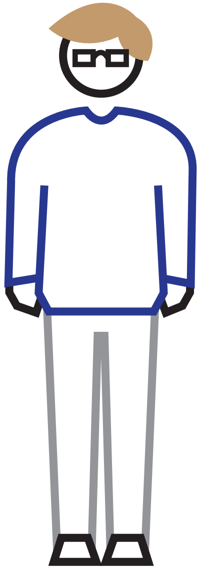

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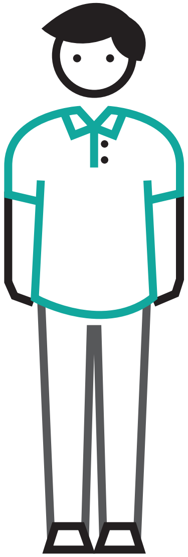

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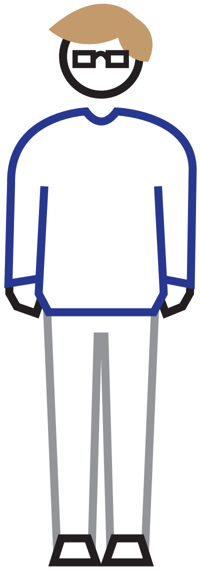

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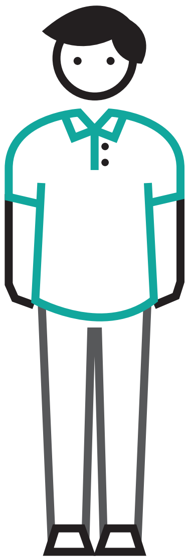

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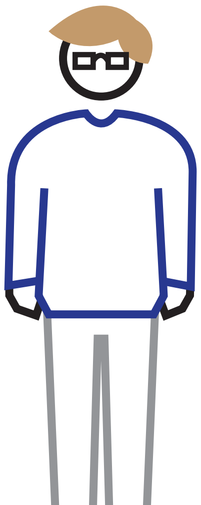

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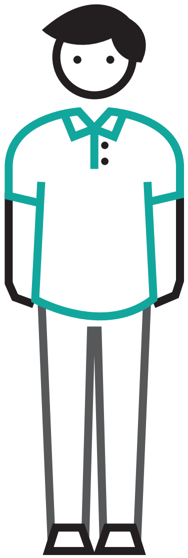

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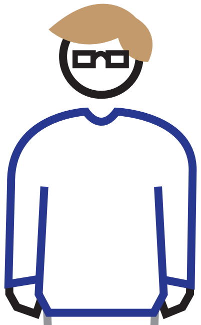

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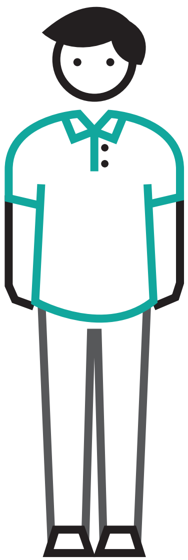

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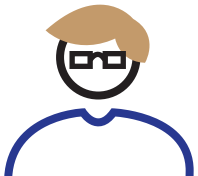

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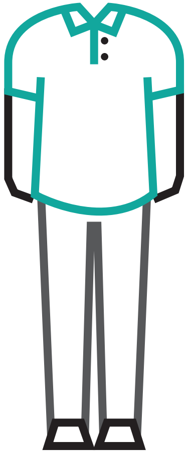

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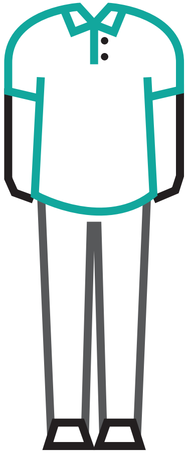

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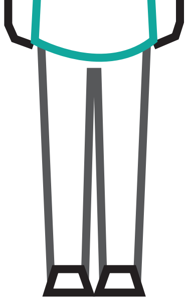

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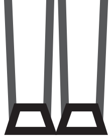

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