- **Theme Music:** **Bob Gramann**

  You're nothin' but a pack of neurons

- **Cartoon:** **Bill Watterson**

  Calvin & Hobbes

Outline

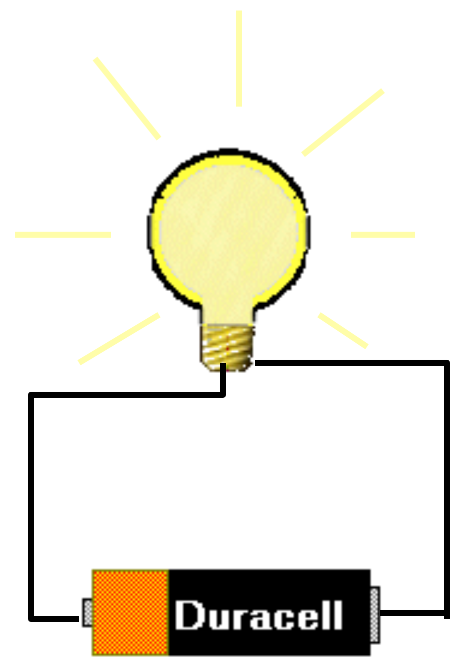
- Moving charge: Current
  - "What really happens"
- The fluid flow model
  - The Hagen-Poiseuille equation
  - Definition of current
  - The nail board analogy
  - The water flow analogy
- Electric current
  - Definition
  - Relation to single charges

Moving Charges

- We know about the forces on charges and we know there are conductors through which charges can move.
- Our next question is how do charges move through a conductor and what laws govern their behavior.
- Two important examples are
  - electrons moving through metal (wires, etc.)
  - ions moving through fluids (Na+, K+,H+, Cl-,…)
- The laws of moving charge were first developed in metals and the methods from there are used as models for ion motion in fluids.

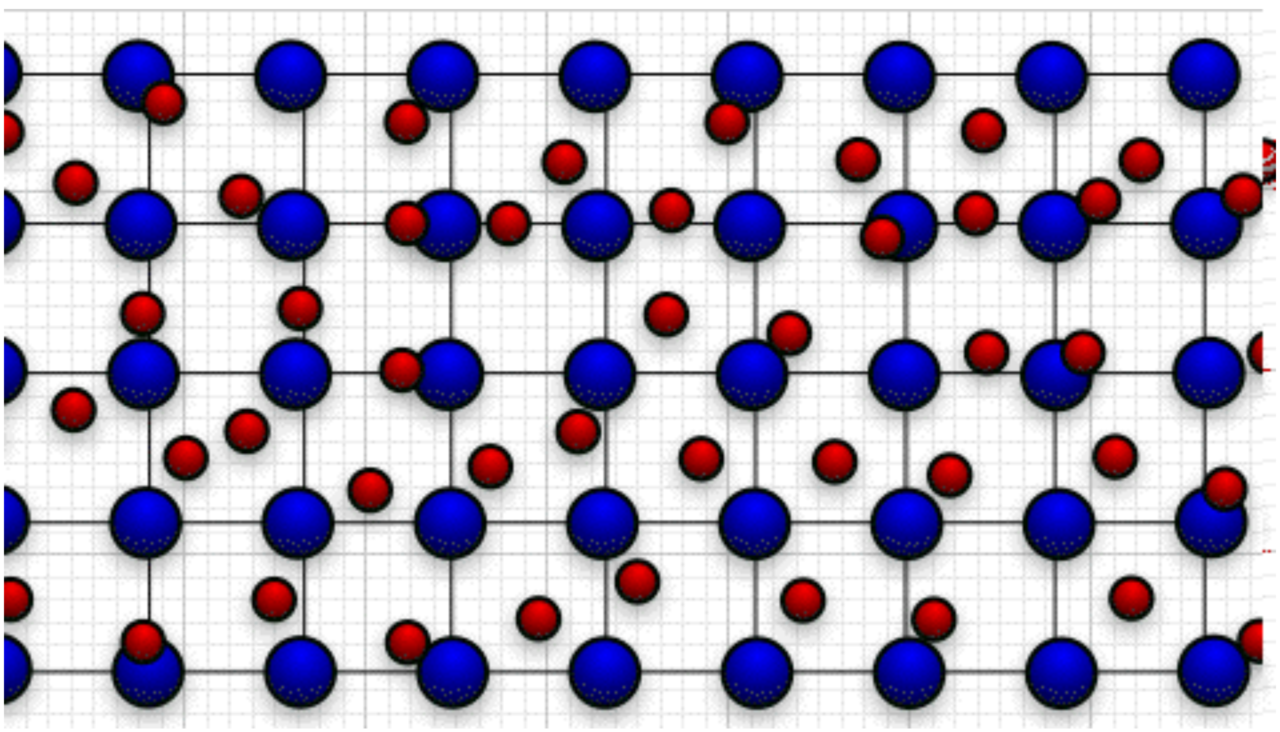
What's going on?

- When we hook up a battery (or any other electric power source) and a bulb, the bulb glows but after a little start up time, stays at a constant brightness.
- We want to understand what's going on here.



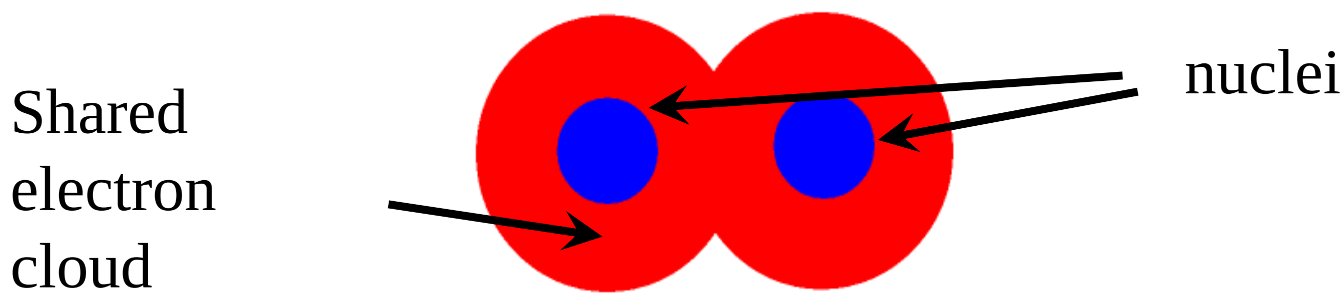
Moving Charges in a Neutral Conductor

- What happens if we arrange charges to put an electric force on a neutral conductor?
  - Positive ions are fixed in a lattice
  - Some negative charges (shared electrons) are free to move



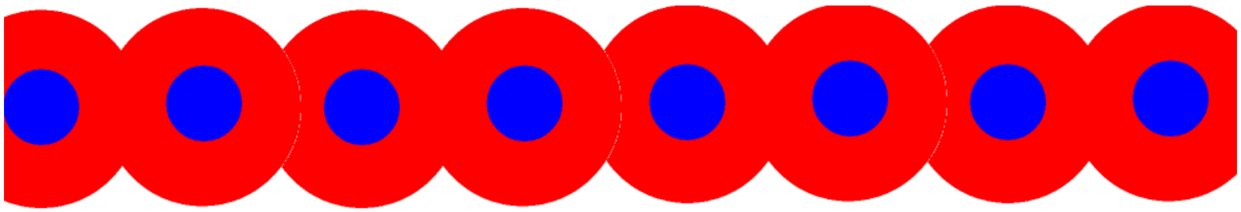
Conductivity in a metal is complicated – and involves the quantum nature of electrons

- What really happens is quantum mechanical – like covalent bonding.



Conduction

- In a crystal of a metal, all the atoms are bonded and some electrons shared.



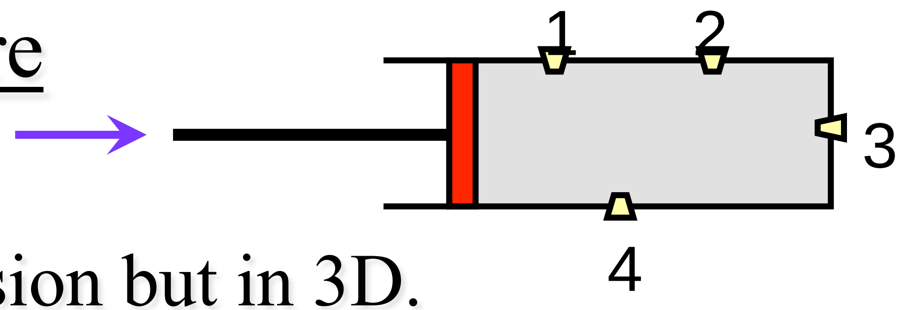
- You can think of some of the electrons as running in each direction along the chain. When an electric field is put on the chain, it shifts the balance and more electrons go one way than the other.
- (In QM, electrons can be "delocalized" – really spread out over many atoms.)

How to think about current?

- Unless we are going to be materials science physicists or electrical engineers, we don't really need to understand the quantum view of conduction.
- Instead, we construct a bunch analogies that have some of the correct features.
  - water flow
  - air flow
  - rope model
  - nail board (electron gas model – Drude)

- These help us make sense of the fundamental laws that govern current flow.

The fluid flow model



- Key concept: <u>Pressure</u>
- Recall:
  - Pressure is like a tension but in 3D.
  - It pushes in all directions at once, so it has no direction.
  - Forces due to pressure occur when you only let it push on one side of an area. Then

$$\vec{F} = P\vec{A}$$

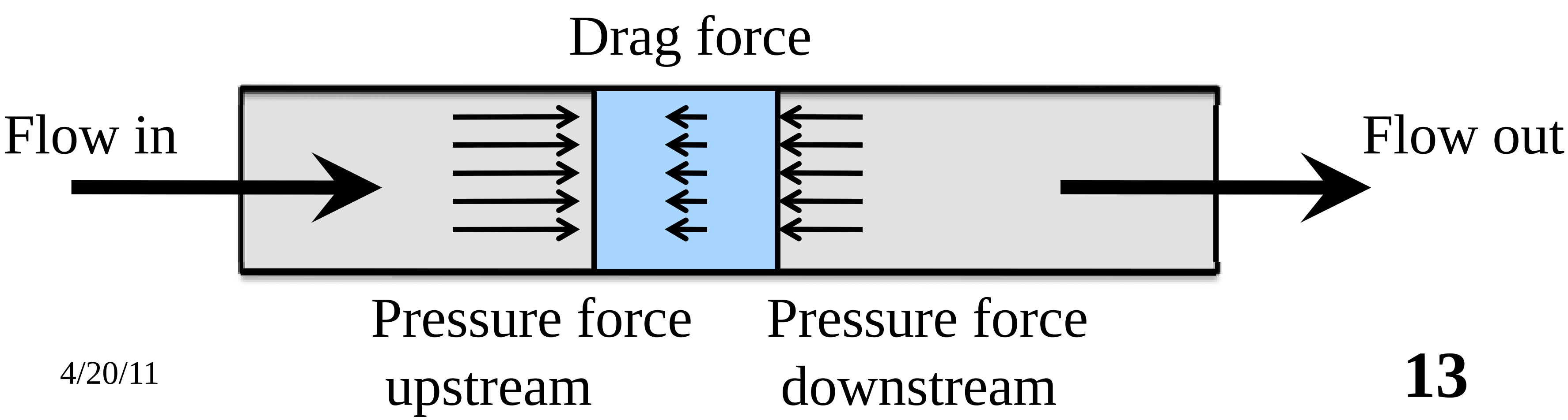
Viscous Drag

- A fluid flowing in a pipe doesn't slip through the pipe frictionlessly.
- The fluid sticks to the walls moves faster at the middle of the pipe than at the edges.
  As a result, it has to "slide over itself" (shear).
- There is friction between layers of fluid moving at different speeds that creates a viscous drag force, trying to reduce the sliding.
- The drag is proportional to the speed and the length of pipe.

$$F_{drag} = 8\pi\mu Lv$$

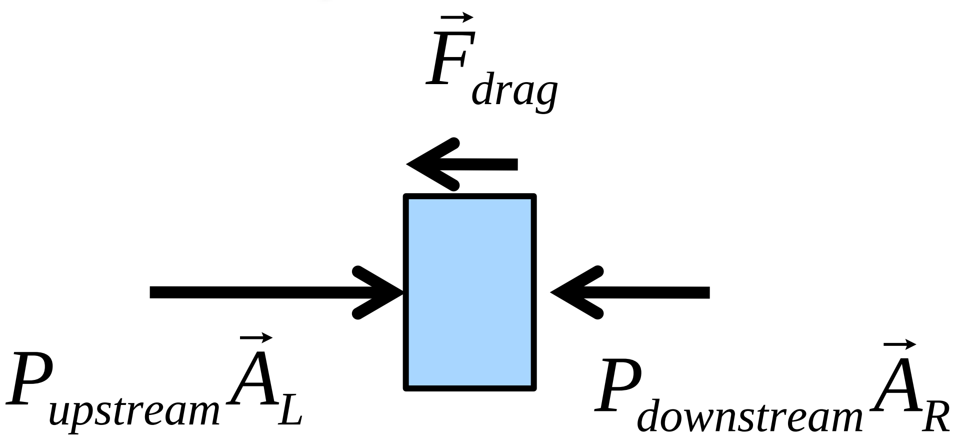
Implication: Pressure drop

- If we have a fluid moving at a constant rate and there is drag, N2 tells us there must be another force to balance the drag.
- The internal pressure in the fluid must drop in the direction of the flow to balance drag.



The Hagen-Poiseuille Law

- If the pressure drop balances the drag (and thereby maintains a constant flow) N2 tells us



Flow: Q = vol/sec = Av

$$\Delta P\, A = 8\pi\mu L v$$

$$\Delta P\, A = 8\pi\mu L\left(\frac{Q}{A}\right)$$

$$\Delta P = \left(\frac{8\pi\mu L}{A^2}\right)Q = \left(\frac{8\mu L}{\pi R^4}\right)Q$$

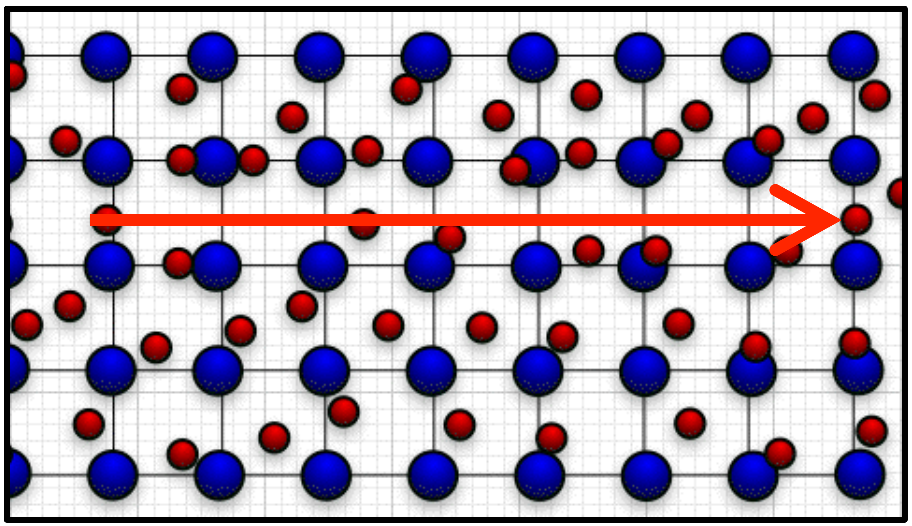
$$\Delta P = QZ$$

Pressure drop

= (Flow)(Resistance)

Moving Charges in a Neutral Conductor

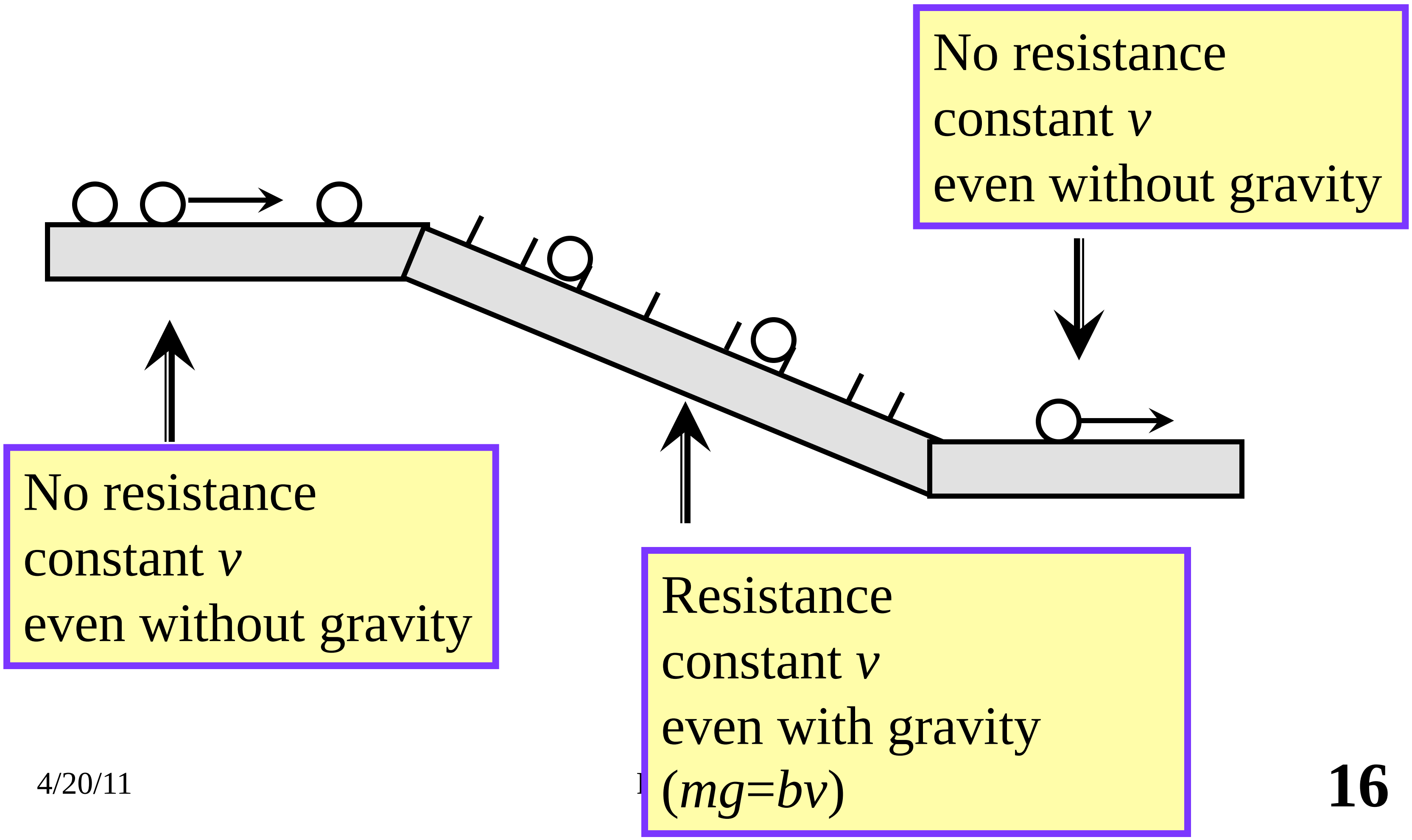
Constant flow of charge through a resistor.
"Resistance" (energy produced – e.g. in lightbulb)



Drag force on the electrons? Guess -*bv*
Must be some kind of "pressure drop" corresponding to the electric force.

Nail Board

- Ping-pong balls and nail board

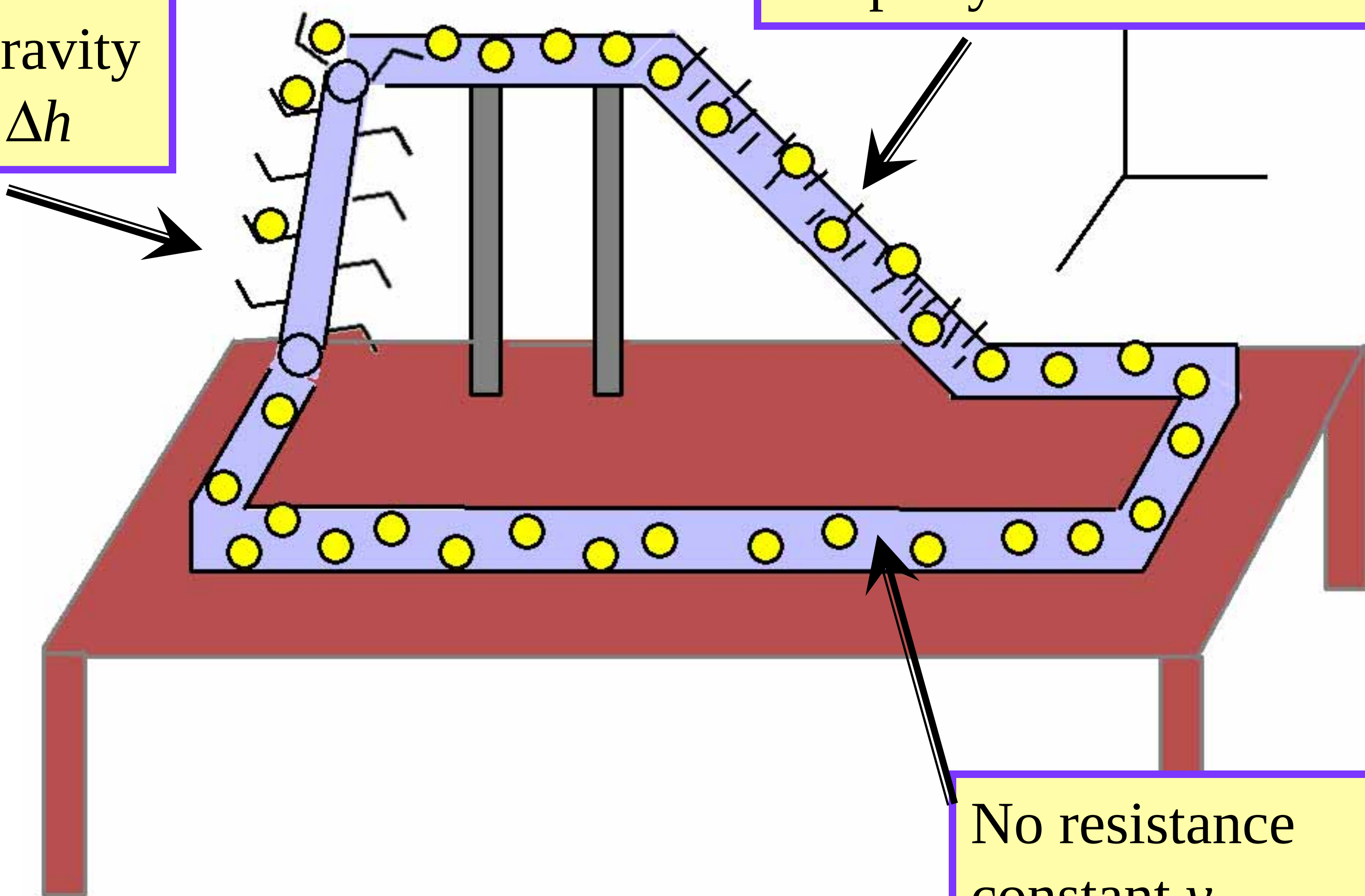


Ping-pong Ball and Nail Board Analogy

- While running horizontally the balls continue with a constant velocity without need for pushing.
- Running downhill through the nails, the continue at the same constant velocity, but are pushed by gravity.
- To get back they have to be carried up by some kind of pump.

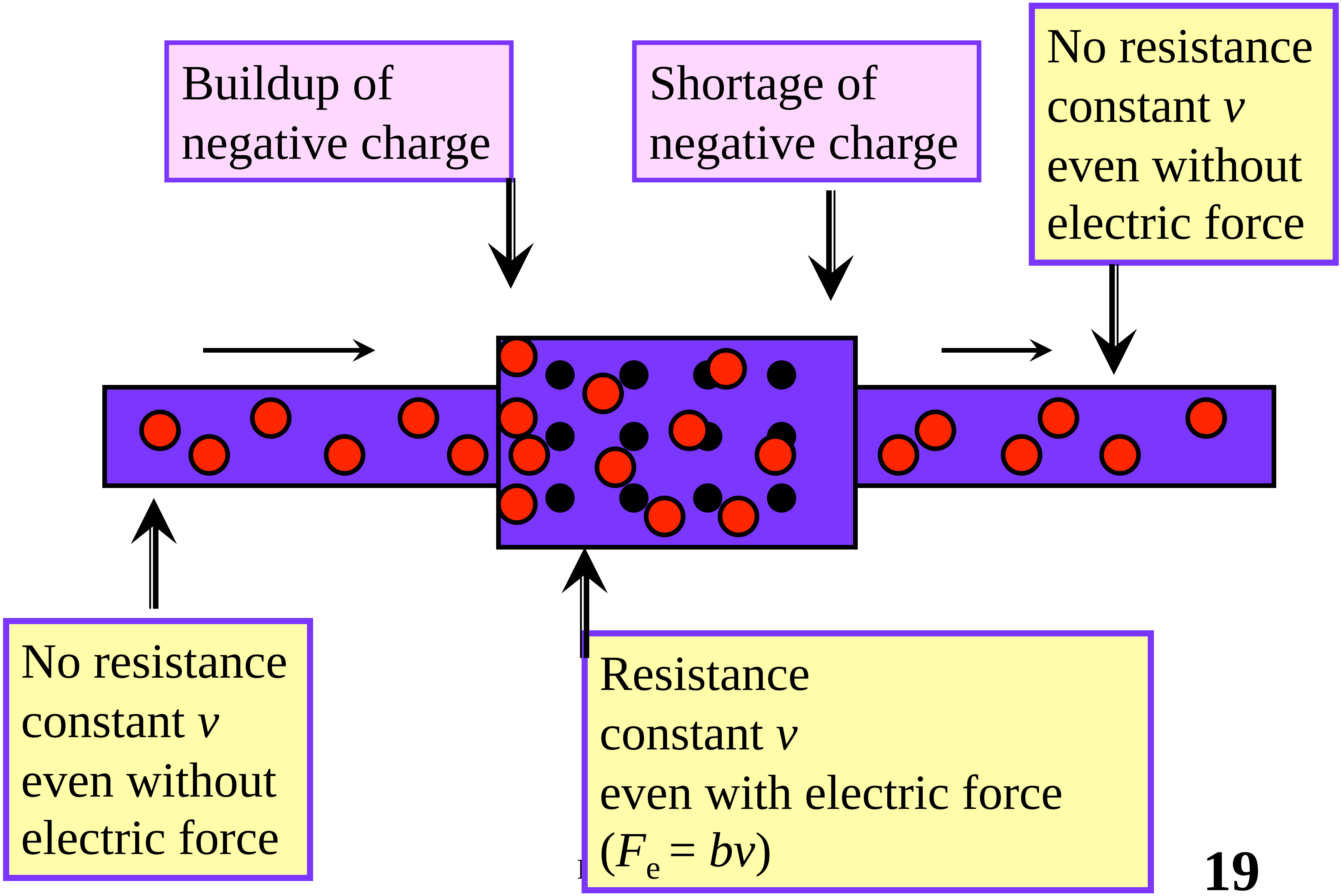
Pump
constant v
Does work
against gravity
Rises by Δh

Resistance constant v
gravity pushing ($mg \sin\theta = bv$)
Drops by Δh.



No resistance
constant v
No change in h

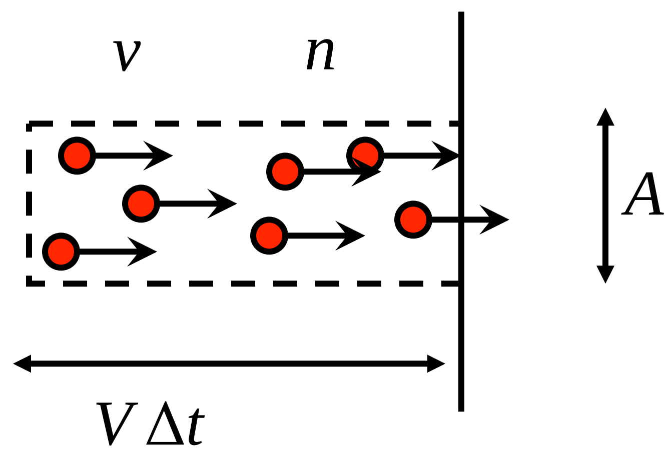
Electric Nail Board



Current

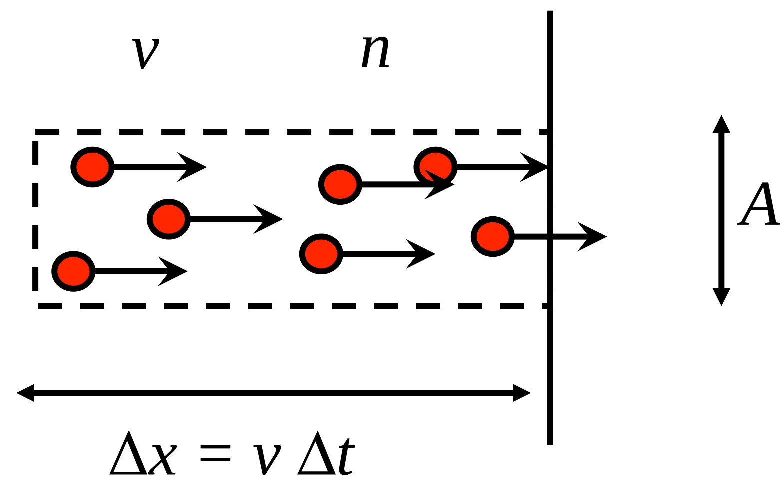
- Consider a wire containing movable current carriers (electrons).
- Define the electric current as rate at which charge moves past a surface.

$$I = \frac{\Delta q}{\Delta t}$$



How Much Current?

- If there is a density of electrons n per unit volume and they are moving with a velocity v, then how many cross the surface in a time Δt?
  - $L = v\,\Delta t$
  - Volume $= LA$
  - $N = n\,(LA) = nAv\,\Delta t$
  - $I = qnAv$



Water Flow Equations

- Matter is moving: describe how much

$$Q = \frac{\Delta(\text{Volume})}{\Delta t} = \frac{A\Delta x}{\Delta t}$$

$$Q = A\,v$$

$$ma = F_p - cv \qquad a = 0 \quad \Rightarrow \quad v = F_p / c$$

- What keeps the mass moving, even though there is resistance?

$$F_p = A\Delta P$$

Charge Flow Equations

- Matter is moving: describe how much

$$I = \frac{\Delta(\text{charge})}{\Delta t} = \frac{\Delta q}{\Delta t}$$

- How does this relate to individual charges?

$$I = nqAv$$

$$ma = F_e - bv \qquad a = 0 \quad \Rightarrow \quad v = F_e/b$$

- What keeps the mass moving, even though there is resistance?

$$F_e = q\frac{\Delta V}{\Delta x}$$