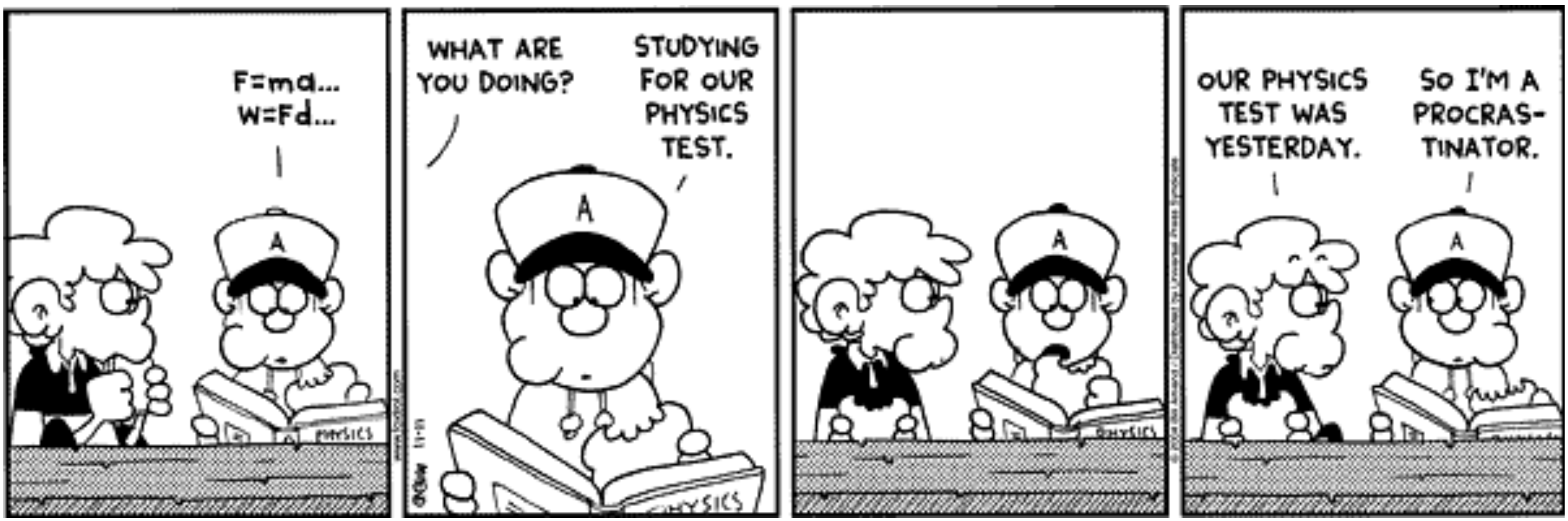
- **<u>Theme Music:</u> Duke Ellington**

  Take the A Train

- **<u>Cartoon:</u> Bill Amend**

  FoxTrot



Foothold ideas:
Energies between charge clusters

- Atoms and molecules are made up of charges.
- The potential energy between two charges is

$$U_{12}^{elec} = \frac{k_C Q_1 Q_2}{r_{12}}$$

No vectors!

- The potential energy between many charges is

$$U_{12...N}^{elec} = \sum_{i<j=1}^{N} \frac{k_C Q_i Q_j}{r_{ij}}$$

Just add up all pairs!

Foothold ideas: Heat & Temperature 1

- Temperature is a measure of how hot or cold something is. (We have a natural physical sense of hot and cold.)
- When two objects are left in contact for long enough they come to the same temperature.
- When two objects of the same material but different temperatures are put together they reach an average, weighted by the fraction of the total mass.
- The mechanism responsible for the above rule is that the same thermal energy is transferred from one object to the other: Q proportional to $m\Delta T$.

Foothold ideas: Heat & Temperature 2

- When two objects of different materials and different temperatures are put together they come to a common temperature, but it is not obtained by the simple rule.
- Each object translates thermal energy into temperature in its own way. This is specified by a density-like quantity, *c*, the specific heat.
- The heat capacity of an object is $C = mc$.
- When two objects of different material and different temperatures are put together they reach an average, weighted by the fraction of the total heat capacity.
- When heat is absorbed or emitted by an object $Q = \pm mc\Delta T$

Foothold ideas: Kinetic Theory

- Newton tell us that motion continues unless something unbalanced tries to stop it, yet motion always dies away.
- The model of matter as lots of little particles in continual motion lets us "hide" energy of motion that has "died away" at the macro level in internal motion.
- Macroscopic energy associated with the motion of a is **coherent**; all parts of the object move in the same way. The object has a net momentum associated with its kinetic energy.
- Internal energy is **incoherent**. The molecules of the object move in random directions. Although individual molecules have kinetic energy and momentum, the net momentum of the object as a result of its thermal energy is zero.
- **Temperature** is basically the average mechanical energy of a molecule.

The Ideal Gas Law

Chemist's form

$$pV = n_{moles}RT$$

$$n_{moles} = \frac{N}{N_A}$$

$$R = k_B N_A$$

Physicist's form

$$pV = Nk_BT$$

$$p = nmv_x^2$$

$$\tfrac{3}{2}k_BT = \tfrac{1}{2}mv^2$$

Energy

- We can now expand our idea of energy to include more forms:
  - 1. Coherent energy of motion (**kinetic**) of the center of mass of an object: ½ mv^2
  - 2. Coherent energy of location relative to other objects (**potential**) of the center of mass.
  - 3. Incoherent internal energy of motion of the parts of an object (**thermal**)
  - 4. Submolecular energy of internal structure (**chemical**)

Systems

- If total energy of everything conserved, conservation isn't useful. What matters is how energy is moved around in relation to parts we care about.
- Define systems:
  - ***Isolated*** – does not exchange energy or matter with the rest of the world.
  - ***Closed*** – exchanges energy but NOT matter with the rest of the world.
  - ***Open*** – exchanges both energy and matter with the rest of the world.

First Law of Thermodynamics: Equations

- Total energy of a system
  (a set of macroscopic objects)

$$E = KE + PE + U$$

Internal energy

- Exchanges of energy between the system and the rest of the universe

$$\Delta E = Q - W$$

Work done by the system on “them”

- Exchanges of energy between the system and the rest of the universe ignoring coherent mechanical energy

$$\Delta U = Q - W$$

Foothold principles: Randomness

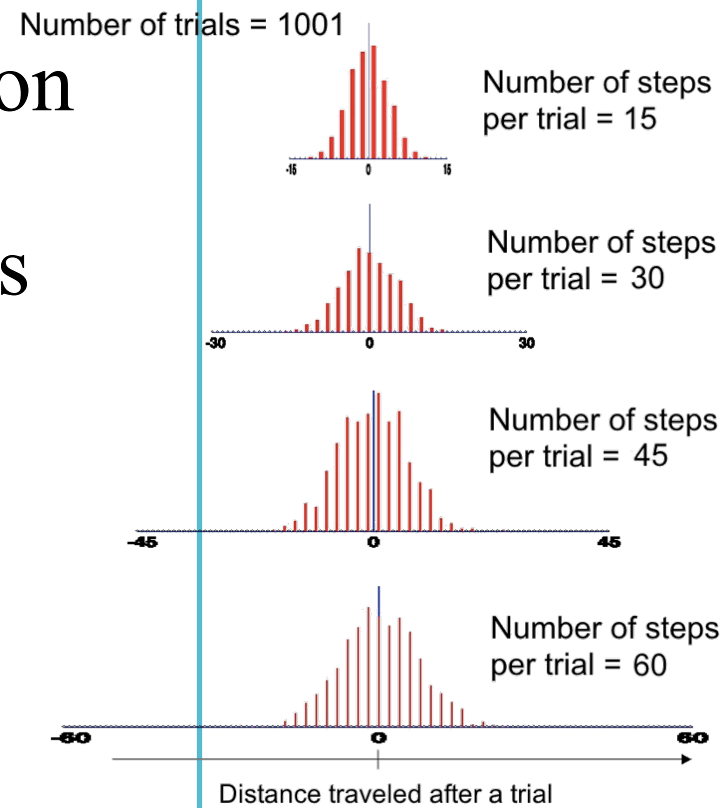
- Matter is made of of molecules in constant motion and interaction. This motion moves stuff around.
- If the distribution of a chemical is non-uniform, the randomness of molecular motion will tend to result in molecules moving from more dense regions to less.
- This is not directed but is an emergent phenomenon arising from the combination of random motion and non-uniform concentration.

Random walk

- As a result of random motion, an initially localized distribution will spread out, getting wider and wider. This phenomenon is called *diffusion*
- The width of the distribution will grow like

$$\left\langle (\Delta r)^2 \right\rangle = 2Dt$$

- *D* is called *the diffusion constant* and has dimensionality $[D] = L^2/T$



Fick's law

- 1D result

$$J = -D\frac{dn}{dx} \qquad D = \tfrac{1}{2}\lambda v_0$$

- For all directions (not just 1D) Fick's law becomes

$$\vec{J} = -D\vec{\nabla} n$$

A vector derivative – the gradient

The gradient

- If we want to take the derivative of a function of one variable, $y = df/dx$, it's straightforward.
- If we have a function of three variables – $f(x,y,z)$ – what do we do?
- The gradient is the **vector derivative.**
  To get it at a point (x,y,z)
  - Find the direction in which f is changing the fastest.
  - Take the derivative by looking at the rate of change in that direction.
  - Put a vector in that direction with its magnitude equal to the maximum rate of change.
  - The result is the vector called $\vec{\nabla} f$

What's a gradient good for?

- Flow is often driven by a change of a scalar quantity:
  - Diffusion – *Fick's law* (concentration gradient)
  - Fluid flow – *HP law* (pressure gradient)
  - Heat flow – *Fourier's law* (temperature gradient)
  - Electric current flow – *Ohm's law* (voltage gradient)
- Force is the gradient of potential energy

$$\vec{F}_{type} = -\vec{\nabla} U_{type}$$

How we develop probabilistic laws

- We model our system as having states that are fully detailed and equally probable (microstates).
- We then count the number of microstates that could correspond to a given state of interest (macrostate).
- We take the probability of the macrostate as proportional to the number of microstates.
- The result is “statistics.”

The Second Law

- When a system is composed of a large number of particles, the system is exceedingly likely to spontaneously move toward the thermodynamic (macro)state that corresponds to the largest possible number of particle arrangements (microstates).

A probabilistic law

- Since the 2^{nd} law relies on probability, it is not an "exact" law.
- It imagines a physical system running through lots of microstates but being most of the time in microstates that correspond to the most probable macrostate.
- The fraction of time that the system is NOT in the most probable macrostate is proportional to $1/\sqrt{N}$.