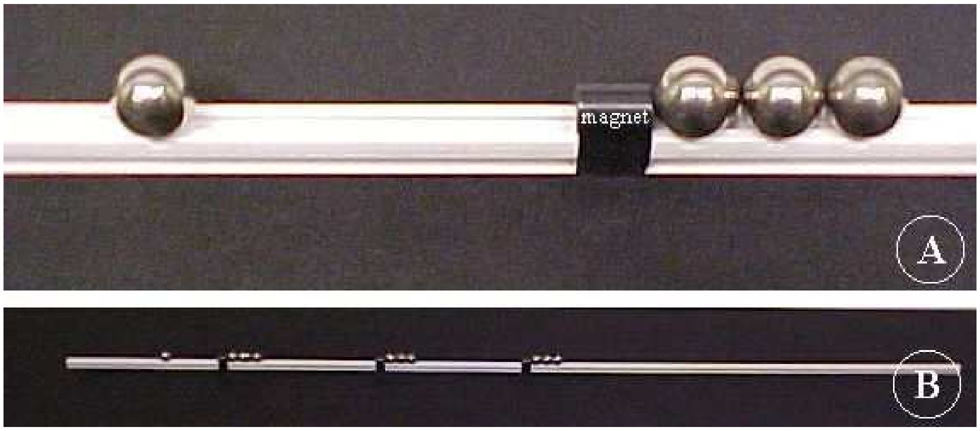
Gauss's rifle

Aim: To show a remarkable demonstration on conservation of mechanical energy. It looks like we are gaining energy!

Subjects: 1M40 (Conservation of Energy)

Diagram:



Equipment:

- Plastic curtain-rail.
- Small ceramic magnets.
- Steel balls.

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Presentation: <u>Introduction</u>

Place one steel ball on the rail. A second ball slowly rolls towards it and there is a collision. The first ball stops and the second ball rolls with a speed equal to that of the starting ball (see Figure1A). Place three steel balls on the rail, touching each other. A fourth ball rolls towards them and there is a collision. The fourth ball stops and the third ball moves away with a speed equal to that of the fourth ball (see Figure 1B).

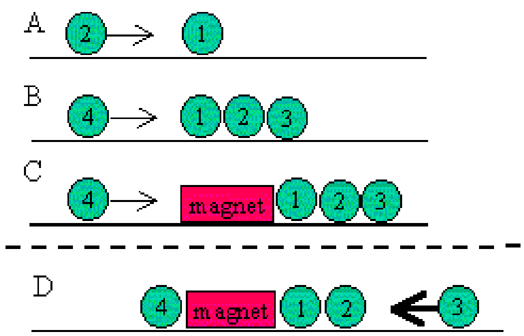

Figure 1

<u>Presentation</u>

A ceramic magnet is added to the setup and firmly fixed to the rail (see Figure 1C). The fourth ball slowly rolls towards the ceramic magnet, hits and ball three rolls away with a much higher speed!

When in figure1C ball 4 is stuck to the magnet, the approaching ball 3 will not launch ball 4.

The demonstration can be made more spectacular by placing more magnet-three-balls combinations, so that the speed increases more and more and more…, making a rifle!(?) (see DiagramB).

Explanation: The magnet exerts an attractive force on the steel balls. When a ball sticks to the magnet a force is needed to make it loose. In terms of potential energy the magnet is a well (see Figure2).

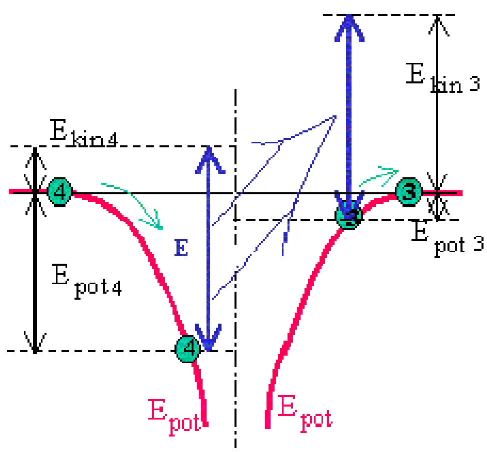

Figure 2

Energy conservation enables a description of the begin- and end-situation (no matter how complicated the proces in between). So we give a description of ball 4 and ball 3:

Gauss's rifle

Total energy before = Total energy after
$U_4 + K_4 + U_3 + K_3 = U'_4 + K'_4 + U'_3 + K'_3$
$0 + K_4 + U_3 + 0 = U'_4 + 0 + 0 + K'_3$
so, $K'_3 = K_4 + U_3 - U'_4$
U_3 and U'_4 are both negative and $[U'_4]>[U_3]$, making $K'_3>K_4$. Ball 3 has the same mass as ball 4, so when $K'_3>K_4$, then ball 3 moves faster than ball 4.
Figure2 visualizes the energy conservation in such a way.

Remarks:

- The demonstration can also be done with 2 or 4 or more steel balls attached to the right side of the magnet. We have the most spectacular effect with three balls.
- The graph of potential energy of the magnetic field is drawn symmetrically. In reality it will be asymmetric, because when balls are attached to the magnet, the shape of the magnetic field will be changed, but it still holds that $\left|E_{pot1}\right| > \left|E_{pot2}\right|$ and the explanation remains the same.
- Extra demonstration
  Is reversing the demonstration possible? (see Figure1D). So, when rolling ball3, can we launch ball 4?
  The preceding demonstration suggests that to make that happen, ball 3 should have a high speed and 4 will be launched with a low speed (reverse the energy-diagram of Figure2). But this will not happen. No matter how high the speed of ball 3, ball 4 will never escape its potential energy well.
  When the high-speed ball 3 hits the magnet-combination it will easily rebound, leaving too little energy to launch ball4. The best we can get is making ball 4 just moving a little to the left (climbing in its well), but then it accelerates quickly back to the magnet.
  It is even easier to make ball 2 escape to the right in this way. So, when ball 3 makes a hit,after that collision ball 2 and ball 3 are "free particles".
  To explain this demonstration we also need to take in consideration conservation of momentum and not only conservation of momentum.
- We experience that after the demonstration, during the break, students love to try several options: It induces a lot of discussions.

Sources:

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 91-97
- Vlaanderen, C.L., Physics Fair, pag. 15-16
- The Physics Teacher, pag. Vol.41(2003) 158-161