The physics of crowds

Crowding affects us almost every day, from supermarket queues to traffic jams. **Timothy Saunders** from EMBL explains why this is interesting to scientists and how to study the phenomenon in class.

The physics of crowds is an active area of research in many fields, from public safety to protein interactions. Crowds occur in many places: people entering stadia, traffic jams, animal migrations (e.g. wildebeest or salmon), and molecular crowding inside cells.

The reasons for crowding are as manifold as their occurrences, and include the density of people, animals or molecules; narrow streets; road works; accidents; lack of visibility; social pressure (when people are uncertain, they tend to follow others); avoidance of danger (groups of animals avoiding predators); limited exit points (wildebeest crossing rivers at shallows during migration); panic (escaping from fire); and rapid velocity changes (traffic-jam formation).

Crowds are a real problem for which the application of physics can be helpful. Crowds have intriguing dynamics: both the behaviour of the individual members of the crowd and of the crowd as a whole must be considered – and this can change rapidly or become unstable. Crowd behaviour can even be counterintuitive. In a traffic jam, for example, the position of the vehicle at the front of the jam often moves further back over time, against the flow of traffic, as the jam propagates through a stream of vehicles[w1].

For more details of the physical phenomena in crowds, see the supplementary online information[w2].

Image courtesy of Hani Nabulsi

A crowd at the Hajj

Image courtesy of Fraz Ismat; image source: Flickr

- Biology
- Physics
- Geography
- Environmental studies
- Mathematics
- Ages 13+

REVIEW

Studies of fluid movement and molecular motion inside cells are presented in a completely innovative way. The concept of crowding is extended to different situations, both at the macro level, such as in human crowding, and the micro level, as when discussing molecules.

The activities, which can be carried out using only basic equipment, are supported by illustrations and websites giving historical information on crowding, pictures and simulations, making them easy to replicate. The development of the lesson plan follows a bottom-up approach, considering initially the experiences of the students and then building upon their experiences to evolve into more detailed analysis of crowding. If the noise might disturb other classes, the activities could be carried out in the playground or sports hall.

Crowding activities are relevant in biology when discussing molecular flow and protein interactions. In physics, they are applicable to fluid movement, velocity changes of traffic flow, and public safety when designing open areas such as stadia and shopping centres. Though it is mainly a scientific concept, crowding could also be used in geography or environmental studies to consider density of people, social pressure and animal migration.

The article and its activities could then be followed up by an individual or group assignment. Students could be asked to design a public stadium, a communal area or even a recreational area for their own school, justifying their arrangements for public safety.

Addressed in different ways, these activities would be suitable for students aged 13 and older. Advanced mathematics students (aged 17+) could use the activity to begin modelling physical processes.

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Teaching crowd formation

The proposed lesson introduces students aged 14 and above to some of the underlying principles of crowds and crowding. In particular, it highlights the need for multiple areas of physics to be used together to tackle such complex phenomena. The lesson can be used to teach phases of matter (because crowds can be both solids and fluids), properties of fluids, forces and interactions, and dynamics. A lesson plan is available online[w2].

Introduction

1. Introduce the topic[w2] and remind the class that crowds do not necessarily involve humans.
2. In groups of 2-5, students should collect examples of crowding and the reasons for crowd formation.
3. Mediate a class discussion to collect the results and reduce the reasons for crowd formation to more general concepts such as those mentioned above (e.g. narrow spaces and panic).

Image courtesy of Rainbirder; image source: Flickr

Wildebeest risking strong currents and crocodiles to cross the Mara river, Kenya

4. Introduce the physical phenomena displayed in crowds[w2]. You can use videos[w3, w4] to help demonstrate these points clearly and refer to the list of examples collected by the class to motivate the discussion. The class should draw analogies between interactions in crowds and other physics concepts (such as electron–electron repulsion, shock / travelling waves and fluid flow).

The following experiments build an intuitive understanding of how different factors affect crowds. They require students to behave sensibly and avoid danger. Stress that students should avoid physical contact during the experiments and that experiments should always be done at a walking pace.

Experiment 1: Leaving the room

This experiment explores how limited access can induce crowding (this is particularly important when designing fire exits) and demonstrates that crowding can be relieved by forcing the crowd into streams.

1. For a class of around 20-25 students, clear an area in the classroom in front of a door: 3-4 m from the door and about 3 m wide (Figure 1A). Adjust the size depending on space and student numbers (allow roughly 0.5 m^2 per student).
2. One student stands outside the door with a stopwatch. The rest line up inside, around the cleared space.

A flock of sheep

Image courtesy of Rainer Sturm / pixelio

Images courtesy of Timothy Saunders

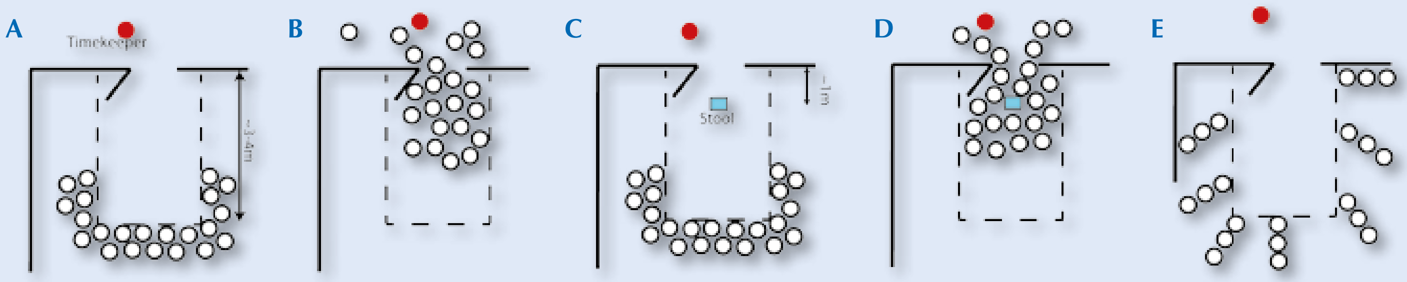

Figure 1: Experiment 1. **(A)** The red spot represents the timekeeping student; black circles represent remaining students. **(B)** Students leave the room together; the timekeeper records how long this takes. **(C)** Repeat **(B)**, but with a stool 1 m from the door. **(D)** The stool causes two streams to form, decreasing exit time. **(E)** Repeat **(B)** with a different initial configuration

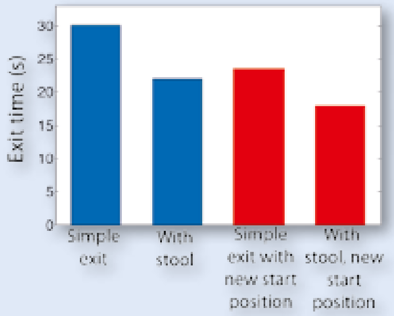

Figure 2: Example distribution of measured times

3. Once ready, the students all start walking at the same time and exit the room.
4. The student outside records starts the stopwatch when the first student leaves the room and stops it after the last student has come through (Figure 1B).
5. Repeat the experiment twice more and record the average exit time over the three repetitions.
6. Next, place a stool 1 m from the door, inside the cleared space (Figure 1C). The students again exit the room, without touching the stool (Figure 1D). Record the average time over three repetitions.
7. The initial configuration of students plays a role in determining the exit time. Ask the students to discuss different initial conditions and how these may reflect more realistic situations (such as people at a fire escape). The class should choose a new initial condition (such as in Figure 1E) and repeat the above experiment.
8. Plot the recorded average times (Figure 2) and discuss reasons for differences in these times in class.

The exit time should be shortest when the stool is present. It breaks the flow of people into two separate streams, which reduces the chance of two people coming very close to one another and makes a blockage less likely. This is an example of counterintuitive physics – an object in the way speeds up the exit rate. Simulations of the above scenarios and a discussion of the underlying physics are available online[w3, w5].

What do these results mean for fire-exit design and fire-safety rules? Should obstacles be put in front of fire exits? This may not always be practical. What would happen if running were allowed? Although this could decrease the exit time, it also increases the chances of an accident – and an injured person at a door would block others from escaping (Figure 3).

Image courtesy of maureenlafleche; image source: Flickr

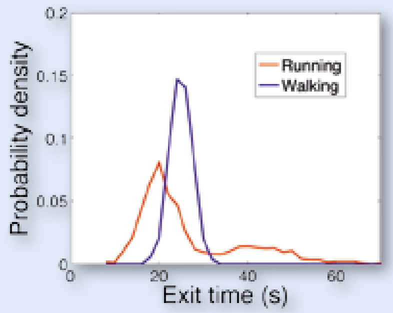

Figure 3: Qualitative comparison of exit times for walking versus running. The mean exit times are similar, but the spread in exit times is much larger for running, a scenario that should be avoided in fire-exit design

Experiment 2: Walking in narrow places

This experiment reveals how space constraints can alter the flow of people or lead to traffic jams. This is particularly relevant in situations where the crowds are densely packed, such as pilgrims to Mecca (on the Hajj)[w2] or in molecular crowding (large proteins in the cytoplasm of cells have a higher folding rate when more densely packed, to save as much space as possible; see McGuffee & Elcock, 2010). Although the experiment is a considerable simplification of such systems, it highlights how crowding can alter collective behaviour.

1. For a class of around 25 students, delimit a 5 x 3 m corridor of clear space, for example using 1 m rules on the floor (Figure 4A). Allow roughly 0.5 m^2 per walker (see Step 2).

A crowd at the entrance to a London Underground station

Image courtesy of Luke Robinson; image source: Flickr

2. Five students are timekeepers (red dots, Figure 4A), each positioned along a 1 x 3 m section of the corridor (chalk can be used to separate the corridor into these regions for clarity) with a stopwatch set to zero. The remaining students are walkers (Mars or Venus symbols), of which one is the target (green filled symbol). Walkers initially position themselves randomly within the area defined by the metre rules, facing one end of the corridor (chosen randomly).
5. Each walker then heads towards the end of the corridor. Once there, they turn and walk to the other end of the corridor, avoiding other walkers.
6. After 30 s (to ensure good mixing), the timekeeper whose area contains the target starts his / her stopwatch. When the target leaves the area, the timekeeper stops his / her stopwatch (but does not reset it!) and the neighbouring timekeeper, whose area the target has just entered, starts his / her stopwatch (Figure 4B). Continue for 2 min and then record the cumulative time on each timekeeper's stopwatch.
7. Next, reduce the width of the corridor by 1 m and repeat the experiment. Continue until the corridor is only 1 m wide (Figure 4C).
8. Plot the recorded times taken by each timekeeper for the different corridor widths (Figure 5).

At low densities (i.e. wide corridor) the target spends roughly the same amount of time in each of the five areas (though slightly longer at the ends, as stopping and turning takes some time). As crowding increases, a traffic jam is likely to form at the centre because this is where velocities are (initially) highest and the narrower corridor makes avoiding other students more challenging – so they are more likely to stop to avoid a collision, thus causing an obstruction. Therefore, for more restricted corridors, the target spends most time in the central regions.

This is an example of how behaviour changes from a free to a restricted system. This is similar in principle to traffic jam formation when the number of lanes is restricted (though obviously the cars are not going in opposite directions in the same lane!). Students may also notice that streams form, akin to streams of pedestrians on the high street[w5]. This happens because it becomes more efficient for someone to follow another person's path rather than forming a new route through the crowd.

Conclusions

Summarise the key results:

- Crowds are dynamic entities, well described by concepts from physics.
- Streaming can relieve crowd pressure. In particular, artificially inducing streaming (using obstacles) can decrease the exit time from crowded areas.
- High initial velocities can induce crowding – it does not always pay to be fast. This is relevant in spatially reduced regions, such as areas with road works or a cell cytoplasm.
- Using the above ideas, physicists have been able to assist in dealing with a number of real-world problems. For example, the annual Hajj has new systems for relieving crowd pressure to attempt to avoid further crowd problems[w2].
- Such solutions require the combination of different physics disciplines (such as fluid mechanics, particle interactions, fluctuations and the role of boundaries) and non-intuitive thinking.

Optional extension

You could have your students write an essay about a particular form of crowding, how physics can explain the observed crowding, and (if appropriate) what can be done to relieve

Image courtesy of Timo Newton-Syms; image source: Flickr

Image courtesy of Timothy Saunders

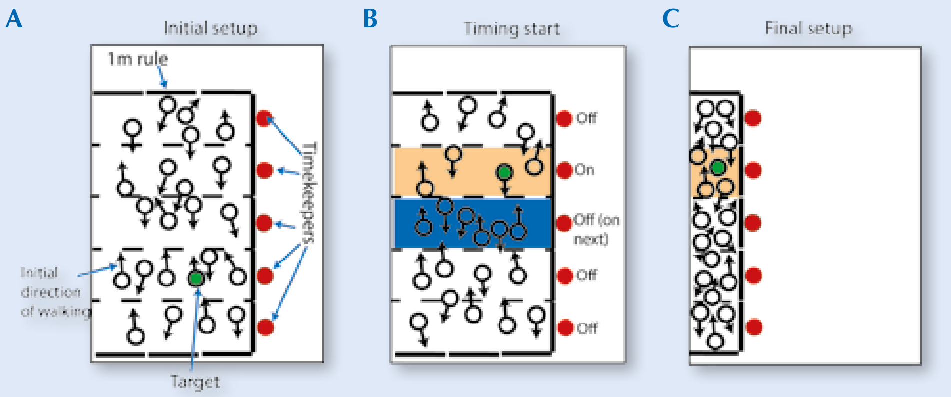

Figure 4: Experiment 2. (**A**) Red dots are timekeepers, the green dot is the target and black circles represent walkers. (**B**) After 30 s of mixing, the timekeeper whose area contains the target starts the stopwatch (orange area). When the target leaves the orange area (into the blue area), the orange timekeeper stops the watch whilst the blue timekeeper starts his / hers. (**C**) Repeat with narrower corridor until the corridor is only 1m wide

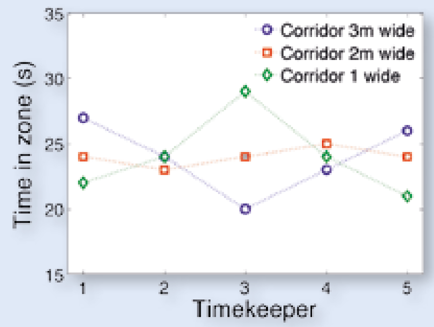

Figure 5: Example of the time distributions measured by the timekeepers

the crowding. Possible examples include the Hajj pilgrimage; design of fire escapes; highway building; town planning; animal migration; diffusion of molecules in cells; or macromolecular crowding in solution.

For mathematically advanced students, the intelligent driver model is a good example of how crowds can be modelled[w6].

Reference

McGuffee SR, Elcock AH (2010) Diffusion, crowding & protein stability in a dynamic molecular model of the bacterial cytoplasm. *PLoS Computational Biology* **6(3)**: e1000694. doi: 10.1371/journal.pcbi.1000694

Web references

w1 – A team of US scientists has set up an informative website to present their simulation data on the formation of traffic jams. It includes a good explanation of their research and results, as well as a number of videos showing how *phantom* traffic jams form. See: http://math.mit.edu/projects/traffic

w2 – For background information on the physics of crowding, including links to online tools, as well as for the lesson plan, see the *Science in School* website: www.scienceinschool.org/2011/issue21/crowding#resources

w3 – Following several stampedes with serious outcomes, scientists from Germany and Saudi Arabia have investigated crowding during the Hajj, which led to changes in the way the crowd is now organised. Their website contains background information and short videos of their analyses, as well as a list of links to other crowd-analysis and simulation studies. See: www.trafficforum.ethz.ch/crowdturbulence

One of the scientists, Dirk Helbing, has since moved to the ETH Zürich, Switzerland. His homepage provides a good collection of videos, links and simulations of crowding and other mass social behaviour such as synchronised clapping. See: www.soms.ethz.ch/research/Videos

w4 – A team of German and Hungarian scientists has simulated escape panic in a computer model. Their free website offers their article published in *Nature* in English and Hungarian, videos simulating various escape scenarios with and without panic or herd effect, a list of major crowd disasters and background information. See: www.panics.org

w5 – For a simulation of how lanes of uniform walking direction form in a street, see: www.trafficforum.org/somsstuff/pedapplets/Corridor.html

w6 – For an explanation of the intelligent driver model, see: www.vwi.tu-dresden.de/~treiber/MicroApplet/IDM.html

Resources

If you found this article useful, you might like to browse the rest of the teaching activities in *Science in School*. See: www.scienceinschool.org/teaching

Timothy Saunders is a post-doctoral researcher at the European Molecular Biology Laboratory in Heidelberg, Germany. His work involves applying concepts from physics to biological problems. Over the past six years he has taught mathematics, physics and biology to students of a range of age groups and abilities. This article grew out of a series of lessons given to adult learners resitting their school biology exams.

To learn how to use this code, see page 65.