LESSON 3

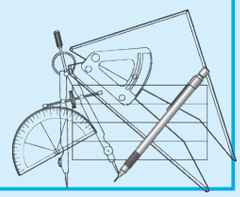
Supersonic Aircraft and Sonic Booms

• In this lesson you will learn the basic principles underlying the phenomenon of a sonic boom.

Before You Read

Do you know...

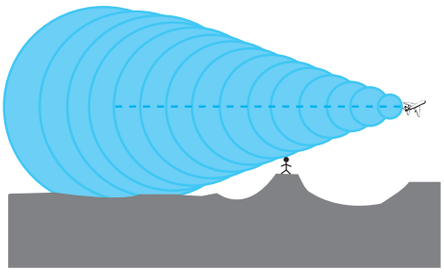
- The cruising speed of a passenger jet is 700~900km/h.
- The speed of sound is 1235 km/h.
- Supersonic airplanes, such as military fighter planes and the Concorde aircraft, can fly faster than the speed of sound.



I *Look at the following diagrams which illustrate the shape of sonic booms. Use the text below to help you understand these pictures.*

1. The fast condensation of water vapor caused by a sonic shock that occurs at sub-sonic speed (due to the breaking of air pressure) causes a vapor cone to form (also called a Prandtl–Glauert singularity), which can be seen with the naked eye.

2. A sonic boom produced by an aircraft moving at M=2.92, calculated from the cone angle of 20 degrees. An observer hears the boom when the shock wave, on the edges of the cone, crosses his or her location.



II *What do you think happens when an object moves faster than the speed of sound? Check (√) your predictions. Discuss your answer with your partner.*

- ❑ You can hear the sonic boom before you see the aircraft.
- ❑ The sonic boom fans out behind the supersonic airplane.
- ❑ A sonic boom is caused by changes in pressure.

Reading

Supersonic Aircraft and Sonic Booms

by 許祖斌教授

Most of us have heard the loud "sonic boom" of a jet airplane soon after it passes overhead. When a low-flying fighter jet **streaks** past at a **tremendous** speed, the noise is particularly loud. But not many people know the basic principles behind the phenomenon of sonic booms. What happens when a source of sound waves, such as a jet aircraft, moves faster than the speed of sound? Such an object is then called "supersonic," which literally means "faster than the speed of sound." The **underlying** reasons for the sonic boom are quite simple, and the phenomenon can be readily explained and **illustrated** with a simple **schematic** figure.

Let us consider the aircraft to be flying in a straight line **trajectory**, and assume that it moves with a speed V_{Plane} from an initial position O at time t_0 to an **arbitrary intermediate** position I at time t_I, and then to its current position P at the present time t_P . We should bear in mind that the aircraft is the source of sound waves at each instant of time, and that the waves, after they are emitted, **propagate radically** outwards from the source in concentric **spheres** at the speed of sound in air, V_{Sound}. The simple relation that the distance traveled by an object in a certain time **interval** is equal to the product of its speed and the time taken is also required. It follows from these rules that at the current moment t_P, the energy of sound which was concentrated at point O when it was emitted by the airplane at t_0 is now spread over a sphere of **radius** $OA = V_{Sound} \times (t_P - t_0)$, while the sound from I is now spread over a smaller sphere of radius $IB = V_{Sound} \times (t_P - t_I)$. The sound from the airplane at t_P is however still localized at P because it has not yet managed to spread anywhere.

It is crucial to note that when the aircraft is supersonic V_{Plane} must be greater than V_{Sound}, and thus the length $OP = V_{Plane} \times (t_P - t_0)$ must be larger than $OA = V_{Sound} \times (t_P - t_0)$. Similarly IP is longer than IB. Note also that we may, in principle, take into account as many intermediate points I as we would like to.

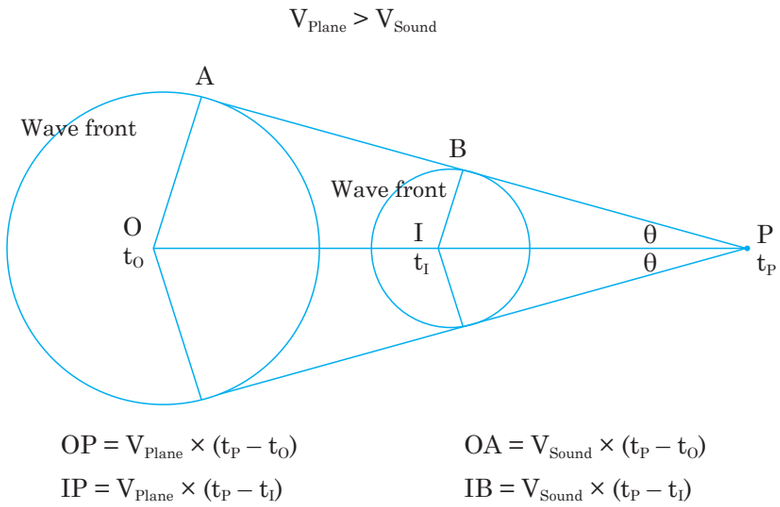
It follows from the above considerations that at time t_P the wavefronts—locations of the concentrations of the energy of the sound waves—of all the sound energy emitted by the plane from O to P, inclusive of all the points in between, taken together form a cone in three dimensions (or a pair of V-shaped lines if we look at a two-dimensional cross section) with P at the **apex** of the cone. The angle between the lines OA and AP is a right angle, i.e. 90 degrees. Similarly, this is true for the angle between IB and BP for any intermediate point I. Thus a little **trigonometry** reveals that the half-angle of the cone, θ, is given by the relation $\sin\theta = OA/OP = IB/IP = V_{Sound}/V_{Plane}$

When a part of the cone of concentrated energy of sound waves sweeps through a bystander as the plane flies on, the shock wave the bystander experiences is responsible for the loud sonic boom that he hears.

A supersonic aircraft is often labeled by its Mach number which is defined as the **ratio** of the speed of the plane to that of sound. Thus a Mach 2.0 jet aircraft is capable of traveling at up to twice the speed of sound. According to our discussion above, the Mach number is also the **reciprocal** of $\sin\theta$.

An interesting **analogy** of sonic boom from supersonic aircrafts occurs when a boat travels faster than the speed of water waves on the surface. The analogy accounts for the V-shaped wave fronts trailing the boat at the apex P. We often observe this in bow waves caused by fast speedboats.

Schematic figure for the discussion



$OP = V_{Plane} \times (t_P - t_O)$ $\quad OA = V_{Sound} \times (t_P - t_O)$

$IP = V_{Plane} \times (t_P - t_I)$ $\quad IB = V_{Sound} \times (t_P - t_I)$

Footnotes for the instructor/student:

1 According to the article, "the distance traveled by an object in a certain time interval is equal to the product of its speed and the time taken," e.g. if you are driving at speed v= 50 km/hr and you started at t_0 =10:00 and the present time is now t_P =12:00, then you have traveled a total distance of $v \times (t_P - t_0)$ = 50km/hr × (12-10) hrs = 100km.

2 Referring to the figure, the sound wave emitted at point O at t_0 has, at present time t_P, spread to the red circle with radius OA= $V_{Sound} \times (t_P - t_0)$. Similarly, sound emitted at I at time t_I will have spread to the circle of radius IB= $V_{Sound} \times (t_P - t_I)$.

3 The distances traveled by an airplane moving at speed V_{Plane} are similarly calculated to be OP = $V_{Plane} \times (t_P - t_0)$ and IP = $V_{Plane} \times (t_P - t_I)$

4 According to the article "it is crucial to note that when the aircraft is supersonic, V_{Plane} must be greater than V_{Sound}; thus the length OP = $V_{Plane} \times (t_P - t_0)$ must be longer than OA = $V_{Sound} \times (t_P - t_0)$. Similarly IP is longer than IB."

5 I is any intermediate position between O and P.

6 If you were to look at where all the sound waves are at the present time t_P, you will realize they are all located at the points marked by the red circles which form a "cone" with the vertex at P.

This article was written by 國立成功大學物理系許祖斌教授，特為本書撰寫此文.

After You Read

Comprehension Check

Circle the correct answer, or write a short answer on the line.

1. What is the main idea of this article?
   a. The distance traveled by an object in a certain time interval is equal to the product of its speed and the time taken.
   b. The trigonometry relation of sin θ is Vsound/Vplane.
   c. The sound energy is concentrated in a cone behind a supersonic aircraft, which is the cause of the sonic boom.
   d. The radius of each wavefront is different.

2. In paragraph 2, what does the ***it*** refer to in the following sentence?
   It follows from these rules that at the current moment t_P, the energy of sound which was concentrated at point O when ***it*** was emitted by the airplane at t_0 is now spread over a sphere of radius OA = $V_{Sound} \times (t_P - t_0)$…

   Answer: _____

3. According to paragraph 4 and the schematic figure, what can be inferred about the sonic boom?
   a. The pitch of the sound heard is higher when the object is moving toward you and lower when the object is moving away.
   b. All of the radii are the same within the triangle AOP.
   c. There can be only two right triangles within the triangle AOP.
   d. There is an infinite number of circles between O and P similar to the circle centered at I.

4. Why does the author mention water waves in the last paragraph?
   a. To explain how sonic booms are caused in water.
   b. To note that sonic booms and water waves have nothing in common.
   c. To point out the similarity between bow waves caused by speedboats and sonic booms from supersonic aircraft.
   d. To explain the underlying reasons for the sonic boom in a more complicated way.

5. In this article, we learned that the sound waves form a cone when an aircraft travels at supersonic speeds. However, what if an object moves at or slower than the speed of sound? What shapes would be formed under those two situations? Research the answers to these questions online and bring your answers for discussion/presentation to the next class.

   Answer: _____

Recognizing Main Points

Match each paragraph with the corresponding answer. Write the letters in the blanks.

Answer	Paragraph No.
1. ____	Paragraph 1
2. ____	Paragraphs 2 & 3
3. ____	Paragraph 4
4. ____	Paragraph 5
5. ____	Paragraph 6
6. ____	Paragraph 7

Main Point
a. The author illustrates the underlying principles of the relation between a supersonic aircraft and its sound by using a diagram.
b. The author explains what the Mach number is.
c. The author explains why an observer can hear a sonic boom.
d. The author introduces the topic and the basic structure of the article.
e. The author shows a mathematical formula based on the given rules.
f. The author uses an analogy to clarify the explanation.

Vocabulary Comprehension

General Vocabulary

For each following group, circle the word that does not belong. The words in grey are general purpose vocabulary.

1	huge	slight	enormous	tremendous
2	underlying	basic	fundamental	inessential
3	demonstrate	hide	illustrate	show
4	table	schematic	figure	diagram
5	arbitrary	unpredictable	random	constant
6	in-between	intervening	distant	intermediate
7	square	sphere	ball	globe
8	period	term	interval	point
9	fraction	proportion	whole	ratio
10	analogy	dissimilarity	resemblance	likeness

ESP Vocabulary

Look at the extracts below from the reading. These words in color are commonly used in the field of science and technology. Match each word with a definition on the right.

____ 1. A jet streaks past at a tremendous speed.

____ 2. An airplane flies in a straight line trajectory.

____ 3. After the sound waves are emitted, they propagate radially outwards from the source.

____ 4. propagate radially outwards from the source

____ 5. When the diameter of a circle is 10 cm, the radius is 5 cm.

____ 6. at the apex of the mountain

____ 7. Sin, cosine and tangent are the most famous trigonometric functions.

____ 8. The Mach number of a supersonic aircraft is the reciprocal of sin θ.

a. spread widely

b. the distance from the center of a circle to its circumference

c. moves very fast and leaves the mark behind

d. dealing with the relations of the sides and angles of triangles

e. a mathematical expression in which one quantity is related to another that their product is one

f. the path of an object flying through the air

g. the top or highest part that forms a point

h. spreading out from the center of a circle

Language Focus

Talking about Ratio

The concept of **ratio** is often used when we want to show notions of part and whole, and so is generally expressed as fractions.

There are different ways of expressing the same ratio. Let's look at the first one that is shown in the reading:

> A supersonic aircraft is often labeled by its Mach number which is defined as *the ratio of the speed of the plane to that of sound*. Thus a Mach 2.0 jet aircraft is capable of traveling at up to twice the speed of sound. (paragraph 6)

The ratio of A to B is … to … is the first way of expressing ratio. So, in this case, a Mach 2.0 jet aircraft gets its number from the following fraction:

$$\frac{\text{the speed of the plane}}{\text{the speed of sound}} = \frac{2}{1}$$

We can therefore understand that "The speed of the plane is twice/two times as fast as that of sound." Another way to say this is "The speed of the plane and the speed of sound are in a ratio of 2 to 1."

Exercise

Read the following fractions and use the three different ways to express the ratio:

(1)

$$\frac{\text{amount of teachers}}{\text{amount of students}} = \frac{1}{50}$$

(2)

$$\frac{\text{amount of unemployment}}{\text{amount of college graduates}} = \frac{1}{10}$$

Corpus Tutorial & Practice: TIME

Learning how to analyze concordance lines is important, because they allow you to observe how to use terms in an appropriate fashion. This section will show you how to discover the important features of a word or phrase. The terms examined here are ***experience in*** *and* ***experience with****.*

experience in

1	… secure, and a fear of a third party after his Progressive **experience in** 1912. He is irreconcilable as ever. …
2	… through with politics – except for writing an account of her **experience in** Congress. I have permission to print it in the Congressional Record and …
3	…, all our Babbitts have learned the value of conservatism by bitter **experience in** recent years, and it is doubtful whether the unreasoning Moody an…
4	… General William Henderson, a 28-year USPS veteran, has no other **experience in** business. Now Henderson is trying to shake up the system…
5	… talks about bringing people together and a man with 24 years' **experience in** national government and international affairs who is extraordinarily…
6	… of foot-and-mouth and mad-cow disease, Kunast – a lawyer with no prior **experience in** agriculture – wants to reform European…
7	… blue-collar workers, but not for a person with 20 years' **experience in** one field. Why cast all that aside? Try something new if you …
8	… usually came from high positions in government or academia. But with **experience in** emergency management, bioterrorism and law enforcement…
9	… she needed a partner to help handle the workload. Both had **experience in** marketing and public relations, but Tom had more background in …
10	… but she did have solid **experience in** food assistance. She worked in the Department of Agriculture from 1989 to …

experience with

1	… be swallowed as short-term medicine. But the U.S. knew, from its **experience with** tariffs and agricultural "parity" payments, WPA, etc. not only…
2	… are the largest fashion for factory machines. After a year's **experience with** painting machinery in contrasting shades, paint-making …
3	experts in war industry. Said President Compton: "My own **experience with** the scientific program of the Government and the technical problem…."

4	… to rally behind Franklin Roosevelt. Said he: "Business had its sad **experience with** The Great Engineer and now it doesn't want to take any chance…"
5	… Peru was considering ways last week of avoiding another **experience with** Japanese infiltration. A Senate committee was studying a bill to prohibit Japanese…
6	… colony, the Empress slapped them down. "England's **experience with** American colonies," she said dryly, "should be a warning to…"
7	… modest about Bill Eitel's and his first **experience with** making vacuum tubes (when Heintz & Kaitman turned them loose on an order…) …
8	… materials and labor) looked with interest at Britain's six months' **experience with** standardized furniture. For, as has happened many a time in the …
9	…, emotional, but brilliant. Stephan's frustrating **experience with** the girl Emma Clery, touched on rather abstractly in the Portrait, is…
10	… or one job), but that was easy enough after their **experience with** Henry Kaiser on Boulder Dam and the San Francisco Bay bridge.

Guiding Question

1. Look at the above concordance lines. What are the words used after the lexical phrase **experience in**?

   Answer: _____

2. According to your findings in 1., what part of speech are these words?

   Answer: _____

3. Could you group the words that you found into different attributes (types or categories)?

   Answer: _____

4. Look at the above concordance lines. What are the words used after the lexical phrase **experience with**?

   Answer: _____

5. According to your findings in 4., what part of speech are these words?

   Answer: _____

6. Could you group the words that you found into different attributes (types or categories)?

   Answer: _____

7. Complete the following table to organize what you found. Also, add the total of times (TOT/frequency) at the end of each preposition based on your search on **TIME**. Then, share your answers with your partners.

Noun	Preposition+ (TOT)	Attributes of the after-preposition-n./n. ph.
experience	in (1010)	experience in + _____
	with (____)	experience with + _____

Make a sentence for **experience in** and **experience with**:

		Sentence
experience	in	
	with	

Tasks

Speaking

Go back to the introduction and the main article, and get clear in your head why a sonic boom is heard when an aircraft goes faster than the speed of sound. You should be able to explain why there is a boom, and what an observer on the ground sees and hears.

Compare your explanation with a partner's. At the end of this activity, you should be able to introduce the concept of a sonic boom to a non-professional, using words that they will easily understand.

Now, imagine you are trying to explain sonic booms to a general audience with no scientific background. Using everyday words and simple analogies and examples, work with your partner(s) to prepare a short presentation.

Writing

Go online to find new and interesting information about sonic boom. Write a 150- to 200-word essay to summarize what you read and found. Remember to write down the source e.g. the address of a website, or just attach the article with your summary.