

SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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Student Materials

Learning Sequence Item:

937

Heat and the Second Law of Thermodynamics

March 1996

Adapted by: Brett Pyle and Paul Mirel

Contents

Lab Activities

1. Be Specific
2. What Has More Heat?
3. The Iron Bar
4. Conduct Yourself Accordingly
5. A Hunka, Hunka Burnin' Cup
6. The Chimney Effect
7. Thank You, Fans!
8. Basking in the Glow
9. The Amazing Straw
10. Beats Me!
11. Drop Zone
12. Steamulous and Response

Readings

1. Benjamin, Count of Rumford's Inquiry Concerning the Source of the Heat Excited by Friction
2. An Account of James Watt and the Steam Engine

Science as Inquiry

Be Specific**Procedure:**

Measure the mass and temperature change of your water according to the teacher's instructions.

Questions:

1. Define calorie in your own words.
2. Define specific heat in your own words.
3. Based on the data you collected for water, calculate the specific heat of water using the following equation:

$$\text{specific heat} = \frac{\text{quantity of heat absorbed (calories)}}{\text{mass (grams) X change in temperature (}^{\circ}\text{C)}}$$

3. Based on the data you collect calculate the specific heat of antifreeze.
4. Based on your calculations for specific heat, would pure water or pure antifreeze absorb more heat from a hot car engine? Explain how you know.
5. Explain why car manufacturers recommend a mix of water and antifreeze to cool a car engine.

Science as Inquiry

What Has More Heat?**Procedure:**

Collect your data for the two substances as instructed by the teacher. Calculate the specific heat of each substance using the following formula:

$$\text{specific heat of metal} = \frac{(\text{mass of water}) (\text{specific heat of water}) (\Delta T \text{ of water})}{(\text{mass of metal}) (\Delta T \text{ of metal})}$$

Questions:

1. Which substance holds more heat? Explain how you know.

Science as Inquiry

The Iron Bar**Procedure:**

Record your observations when you placed the paper-wrapped metal bar over the flame.

Questions:

1. Explain why the paper behaved as it did.
2. Explain what could cause any differences observed when you repeated the experiment with a wooden dowel rod.

Science as Inquiry

Conduct Yourself Accordingly**Questions:**

1. Compare and explain your observations of what it felt like when you held your hand in the air 6 cm from the flame versus holding the paper clip 6 cm from the flame.
2. Describe any changes in the paper clip other than temperature.
3. Describe in your own words the difference between a heat conductor and a heat insulator.
4. Explain why the air and the paper clip do not conduct heat equally.

Science as Inquiry

A Hunka, Hunka Burnin' Cup**Questions:**

1. Describe what happened when you placed the paper cup of water over the flame.
2. Describe what happened when you placed the strainer full of paper over the flame.
- 3 Explain your observations in numbers 2 and 3.
4. If you place a nail into a potato and place it in the oven, it will bake faster than a potato without a nail. Explain.
5. Explain why ice will form on bridges in the winter before it will form on the roadway.

Science as Inquiry

The Chimney Effect**Procedure:**

Make a drawing of the laboratory setup and show the pattern of movement of the smoke from the incense.

Questions:

1. Explain why the smoke behaves as it does.
2. Think of a fireplace in a home. Explain where the air comes from to keep the fire burning. Explain where the heated air from a fireplace goes. Tell whether or not a fireplace is a good room heater from a convection standpoint.

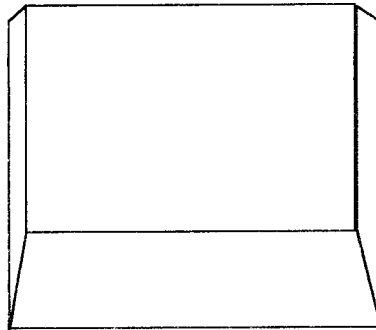
Science as Inquiry

Thank You, Fans!**Procedure:**

Record your observations of what you see occurring during the experiment.

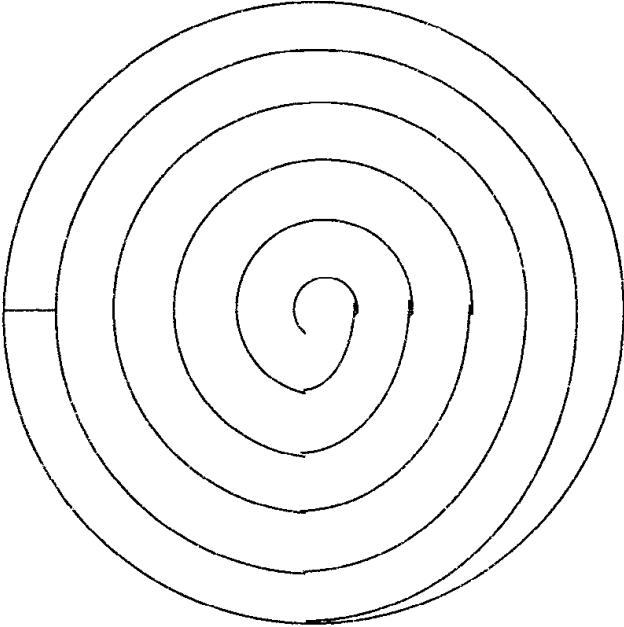
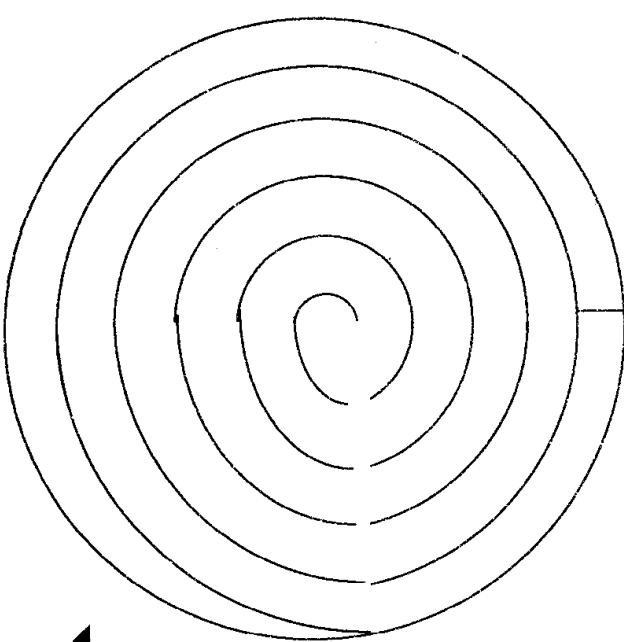
Questions:

1. What caused the spiral to behave as it did?
2. Where would you expect the hottest part of a room to be? Explain why.
3. If you were building a house and you were installing air conditioning vents in the rooms, show on the diagram where you would place them. Explain why you placed them where you did.

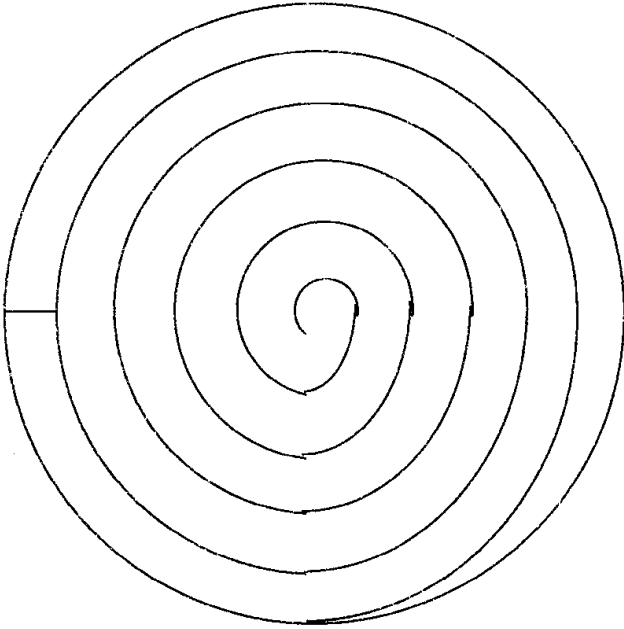
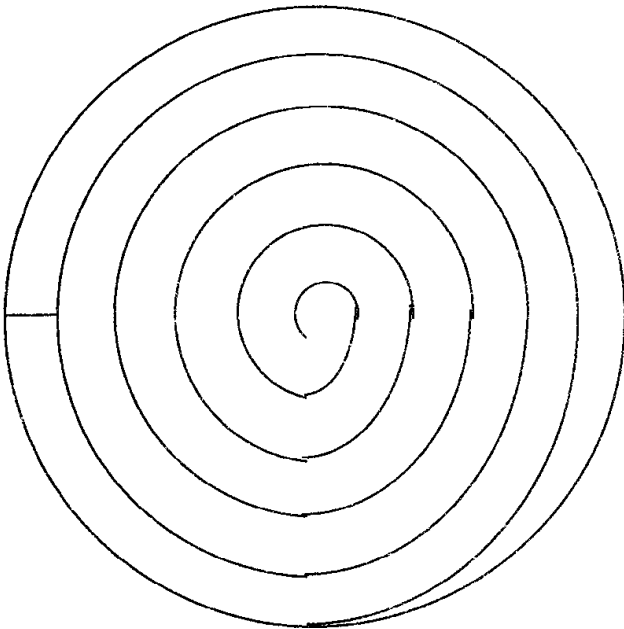


4. In the summer, ceiling fans lift air up from the floor. Explain what this does to the temperature of the room and how this relates to convection.

Spiral patterns for lab. Cut along all lines shown.



↖ This diagram for left-handed students.
(It is easier to cut out)



Science as Inquiry

Basking in the Glow**Procedure:**

On the diagram below, draw a line around the bottom and sides of the candle flame showing where the wax began to melt.

**Questions:**

1. Explain why the melting of the wax could not be caused by heat convection.
2. Explain why the melting of the wax could not be caused by heat conduction.
3. Explain how heat is transferred by radiation.
4. Explain how you know radiation can move through a vacuum.

Science as Inquiry

The Amazing Straw**Procedure:**

Record your observations when the straw is placed in the sun or under a light.

Questions:

1. Explain why the colored water in the straw behaves as it does.
2. Explain the effect of blackening the straw. What was the effect of adding the aluminum foil?
3. Explain how the results of this experiment relate to the gas laws you studied in unit 9.02.

Science as Inquiry

Beats Me!**What happens to the temperature of a bowl of water when stirred?****Overview:**

My best advice for this activity is to just beat it! Can stirring something increase its temperature?

Procedure:

Use a thermometer to measure the temperature of water in a bowl or jar. Then, using an eggbeater or whisk, stir the water (or close the jar and shake it). After a few minutes of continuous agitation, measure the temperature of the water again.

Questions:

1. What happened to the temperature of the water as a result of stirring?
2. What do you think would happen if you stirred more vigorously or less vigorously?
3. What other mechanical methods could you use to affect the temperature of the water?
4. Would the temperature change be faster or slower if you used a more viscous fluid (such as oil or molasses)?

Science as Inquiry

Drop Zone**What happens to the temperature of a bag of pennies if the bag is repeatedly dropped?****Overview:**

Pennies from heaven? This activity will involve you in dropping bags of pennies to see if you can produce any heat.

Procedure:

Your teacher will provide you with a bag of pennies. Use a thermometer to measure the temperature of the pennies inside the bag. Seal the bag securely and drop it to the floor—about 100 times. Unseal the bag and measure the temperature again.

Questions:

1. What happened to the temperature of the pennies as a result of repeated dropping?
2. Why do you think the instructions call for 100 drops? What would happen differently if you only dropped the bag once?
3. How do you think the temperature of the pennies would change if you threw the bag down instead of just dropping it? (If trying this, keep in mind that the bag may break if you throw it too hard—and that you will have to clean up the scattered pennies!)
4. The strength of the impacts \propto the number of impacts is a measure of how much mechanical energy you put into the pennies. How is the amount of mechanical energy you add related to the change in temperature of the pennies? Record your observations when the straw is placed in the sun or under a light.

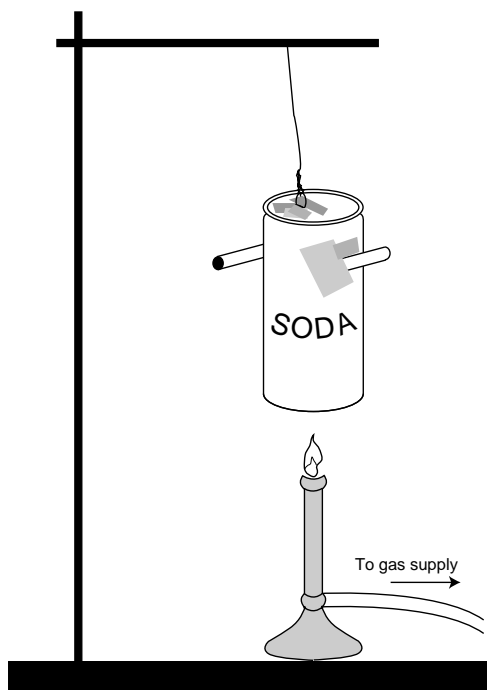
Science as Inquiry

Steamulous and Response**How do we know invisible radiation exists?****Overview:**

Can the reverse of the first activity be true? Can heat produce a movement? Construct this steam can and find out.

Procedure:

Set up the can or flask (provided) so that it hangs freely from the stand as shown below. Add some water, seal the top of the can tightly, and light the burner.

**Questions:**

1. What did the can do when the water started to boil?
2. Can you think of any practical uses for this setup?
3. Why does the can reverse its motion sometimes?
4. What other devices do you know of that use the heat from burning fuel to produce motion?

History and Nature of Science

Benjamin, Count of Rumford's Inquiry Concerning the Source of Heat Excited by Friction

Read January 25, 1798

It frequently happens, that in the ordinary affairs and occupations of life, opportunities present themselves of contemplating some of the most curious operations of nature; and very interesting philosophical experiments might often be made, almost without trouble or expense, by means of machinery contrived for the mere mechanical purposes of the arts and manufactures.

I have frequently had occasion to make this observation; and am persuaded, that a habit of keeping the eyes open to every thing that is going on in the ordinary course of the business of life has oftener led, as it were by accident, or in the playful excursions of the imagination, put into action by contemplating the most common appearances, to useful doubts, and sensible schemes for investigation and improvement, than all the more intense meditations of philosophers, in the hours expressly set apart for study.

It was by accident that I was led to make the experiments of which I am about to give an account; and, though they are not perhaps of sufficient importance to merit so formal an introduction, I cannot help flattering myself that they will be thought curious in several respects, and worthy of the honour of being made known to the Royal Society.

Being engaged laterly, in superintending the boring of cannon, in the workshops of the military arsenal at Munich, I was struck with the very

considerable degree of heat which a brass gun acquires, in a short time, in being bored; and with the still more intense heat (much greater than that of boiling water, as I found by experiment), of the metallic chips separated from it by the borer.

The more I meditated on these phenomena, the more they appeared to me to be curious and interesting. A thorough investigation of them seemed even to bid fair to give a farther insight into the hidden nature of heat; and to enable us to form some reasonable conjectures respecting the existence, or non-existence, of an igneous fluid: a subject on which the opinions of philosophers have, in all ages, been much divided.

In order that the Society may have clear and distinct ideas of the speculations and reasonings to which these appearances gave rise in my mind, and also of the specific objects of philosophical investigation they suggested to me, I must beg leave to state them at some length, and in such manner as I shall think best suited to answer this purpose.

From whence comes the heat actually produced in the mechanical operation above mentioned?

Is it furnished by the metallic chips which are separated by the borer from the solid mass of metal?

If this were the case, then, according to the modern doctrines of latent heat, and of caloric, the capacity for heat of the parts of the metal, so reduced to chips, ought not only to be changed, but

the change undergone by them should be sufficiently great to account for all the heat produced.

But no such change had taken place; for I found, upon taking equal quantities, by weight, of these chips, and of thin slips of the same block of metal separated by means of a fine saw, and putting them, at the same temperature, (that of boiling water), into equal quantities of cold water, (that is to say, at the temperature of 59½°F) the portion of water into which the chips were put was not, to all appearance, heated either less or more than the other portion, in which the slips of metal were put.

This experiment being repeated several times, the results were always so nearly the same, that I could not determine whether any, or what change, had been produced in the metal, in regard to its capacity for heat, by being reduced to chips by the borer.⁵

These engines, then, differed in nothing from the ancient ones, except in the application of W.'s principles as set forth in his specification.

It was found that the external cylinder, or steam-case, was very expensive. The method of covering the cylinder itself with a lid or cover, (which had been used in some of the models), and conveying the steam to the lower end of the cylinder by a pipe, was adopted, and a less expensive method of applying the envelope of steam was used. Other kinds of regulators were invented, and the whole mechanism of the engine was gradually improved, and these improvements have been progressive for the last twenty-one years. Some of them W. has secured by other patents, but many of the most essential he has left free, and by means of them Newcomen's engines have been improved to his loss.

It will now, it is hoped, appear to the candid that W. has not willfully concealed his invention by a false specification, but has set forth the nature of the same, and the means of performing it. He has told what he had invented; and it could not have been expected that he should have described mechanism already known to all practitioners, or not then invented.

W.'s invention is merely a contrivance to prevent cooling the cylinder, and to make the

vacuum more perfect by condensing the steam in a vessel distinct from the cylinder itself; this is the nature of the invention. The means of keeping the cylinder warm—the substitution of the powers of steam for those of the atmosphere—of grease, & c., in place of water to keep the piston tight—and the drawing out the air, & c., by means of pumps—are merely aids in performing the principal object. This ought to be kept in view in judging of the specification; also that W. supposed it to be addressed to mechanics and philosophers, and not to the ignorant.

From hence it is evident, that the heat produced could not possibly have been furnished at the expense of the latent heat of the metallic chips. But, not being willing to rest satisfied with these trials, however, conclusive they appeared to me to be, I had recourse to the following still more decisive experiment.

Taking a cannon, (a brass six-pounder), cast solid, and rough as it came from the foundry, [see fig. 1, Tab. IV] and fixing it (horizontally) in the machines used for boring, and at the same time finishing the outside of the cannon by turning, [see fig. 2.] I caused its extremity to be cut off; and, by turning down the metal in that part, a solid cylinder was formed 7¾ inches in diameter, and 98½ inches long; which, when finished, remained joined to the rest of the metal (that which, properly speaking, constituted the cannon), by a small cylindrical neck, only 2½ inches in diameter, and 38½ inches long.

This short cylinder, which was supported in its horizontal position, and turned round its axis, by means of the neck by which it remained united to the cannon, was now bored with the horizontal borer used in boring cannon; but its bore, which was 3.7 inches in diameter, instead of being continued through its whole length (9.8 inches) was only 7.2 inches in length; so that a solid bottom was left to this hollow cylinder, which bottom was

5 As these experiments are important, it may perhaps be agreeable to the Society to be made acquainted with them in their details. One of them was as follows: To 4,590 grains of water, at the temperature of 59-1/2°F (an allowance as compensation, reckoned in water, for the capacity for heat of the containing cylindrical tin vessel, being included), were added 1,106-1/8 grains of gunmetal in thin slips, separated from the gun by means of a fine saw, being at the temperature of 210°F. When they had remained together 1 minute, and had been well stirred, about, by means of a small rod of light wood, the heat of the mixture was found to be = 63°.

2.6 inches in thickness.

[This cavity is represented by dotted lines in fig. 2; as also in fig. 3 where the cylinder is represented on an enlarged scale.]

This cylinder being designed for the express purpose of generating heat by friction, by having a blunt borer forced against its solid bottom at the same time that it should be turned round its axis by the force of horses, in order that the heat accumulated in the cylinder might from time to time be measured, a small round hole, [see d, e, fig. 3] 0.37 of an inch only in diameter, and 4.2 inches in depth, for the purpose of introducing a small cylindrical mercurial thermometer, was made in it, on one side, in a direction perpendicular to the axis of the cylinder, and ending in the middle of the solid part of the metal which formed the bottom of its bore.

The solid contents of this hollow cylinder, exclusive of the cylindrical neck by which it remained united to the cannon, were 3853/4 cubic inches, English measure; and it weighted 113.13 lb avoirdupois: as I found, on weighing it at the end of the course of experiments made with it, and after it had been separated from the cannon with which, during the experiments, it remained connected.

Experiment No. 1⁶

This experiment was made in order to ascertain how much heat was actually generated by friction, when, a blunt steel borer being so forcibly shoved (by means of a strong screw) against the bottom of the bore of the cylinder, that the pressure against it was equal to the weight of about 10,000 lb avoirdupois, the cylinder was turned round on its axis, (by the force of horses), at the rate of about 32 times in a minute.

[This machinery, as it was put together for the experiment, is represented by fig. 2.] W. is a strong horizontal iron bar, connected with proper machinery carried round by horses, by means of which the cannon was made to turn round its axis.

To prevent, as far as possible, the loss of any part of the heat that was generated in the experiment, the cylinder was well covered up with a fit coating of thick and warm flannel, which was

carefully wrapped round it, and defended it on every side from the cold air of the atmosphere. [This covering is not represented in the drawing of the apparatus, fig. 2.]

I ought to mention, that the borer was a flat piece of hardened steel, 0.63 of an inch thick, 4 inches long, and nearly as wide as the cavity of the bore of the cylinder, namely, 3 1/2 inches. Its corners were founded off at its end, so as to make it fit the hollow bottom of the bore; and it was firmly fastened to the iron bar (m) which kept it in its place. The area of the surface by which its end was in contact with the bottom of the bore of the cylinder was nearly 2 1/3 inches. This borer, which is distinguished by the letter e, is represented in most of the figures.

At the beginning of the experiment, the temperature of the air in the shade, as also that of the cylinder, was just 60°F.

At the end of 30 minutes, when the cylinder had made 960 revolutions about its axis, the horses being stopped, a cylindrical mercurial thermometer, whose bulb was 32 1/100 of an inch in diameter, and 3 1/4 inches in length, was introduced into the hole made to receive it, in the side of the cylinder, when the mercury rose almost instantly to 130°.

Though the heat could not be supposed to be quite equally distributed in every part of the cylinder, yet, as the length of the bulb of the thermometer was such that it extended from the axis of the cylinder to near its surface, the heat indicated by it could not be very different from that of the mean temperature of the cylinder; and it was on this account that a thermometer of that particular form was chosen for this experiment.

To see how fast the heat escaped out of the cylinder, in order to be able to make a probable conjecture respecting the quantity given off by it, during the time the heat generated by the friction was accumulating, the machinery standing still, I

⁶ From this experiment the specific heat of the metal, calculated according to the rule given by Dr. Crawford, turns out to be = 0.111,0; that of water being = 1.000,0. An experiment was afterward made with the metallic ships, as follows: To the same quantity of water as was used in the experiment above mentioned, at the same temperature (viz. 59-1/2°), and in the same cylindrical tin vessel, were now put 1,016-1/8 grains of metallic chips of gunmetal, bored out of the same gun from which the slips used in the foregoing experiment were taken, and at the same temperature (210°). The heat of the mixture, at the end of the 1 minute, was just (63°) as before; consequently the specific heat of these metallic chips was = 0.111,0. Each of the above experiments was repeated three times, and always with nearly the same results.

suffered the thermometer to remain in its place near three quarters of an hour, observing and noting down, at small intervals of time, the height of the temperature indicated by it.

Having taken away the borer, I now removed the metallic dust, or rather cakey matter, which had been detached from the bottom of the cylinder by the blunt steel borer, in this experiment; and, having carefully weighed it, I found its weight to be 837 grains Troy.

Is it possible that the very considerable quantity of heat that was produced in this experiment (a quantity which actually raised the temperature of about 113 lb of gun-metal at least 70 degrees of Fahrenheit's thermometer, and which, of course, would have been capable of melting 61½ lb of ice, or of causing near 5 lb of ice-cold water to boil), could have been furnished by so inconsiderable a quantity of metallic dust? and this merely in consequence of a change of its capacity for heat?

As the weight of this dust (837 grains Troy) amounted to no more than 1⁄948th part of that of the cylinder, it must have lost no less than 948 degrees of heat, to have been able to have raised the temperature of the cylinder 1 degree; and consequently it must have given off 66,360 degrees of heat, to have produced the effects which were actually found to have been produced in the experiment!

But, without insisting on the improbability of this supposition, we have only to recollect, that from the results of actual and decisive experiments, made for the express purpose of ascertaining that fact, the capacity for heat, of the et al., of which great guns are case, is not sensibly changed by being reduced to the form of metallic chips, in the operation of boring cannon; and there does not seem to be any reason to think that it can be much changed, if it be changed at all, in being reduced to much smaller pieces, by means of a borer that is less sharp.

If the heat, or any considerable part of it, were produced in consequence of a change in the capacity for heat of a part of the metal of the cylinder, as such change could only be superficial, the cylinder would by degrees be exhausted; or the

Thus at the end of	The heat, as shown by the thermometer was
4 min.	126°
after 5 min., always reckoning from the first observation, at the end of 7 min.	125° 123°
12 min.	120°
14 min.	119°
16 min.	118°
20 min.	116°
24 min.	115°
28 min.	114°
31 min.	113°
34 min.	112°
37 1/2 min.	111°
and when 41 min. had elapsed	110°

quantities of heat produced, in any given short space of time, would be found to diminish gradually, in successive experiments.

To find out if this really happened or not, I repeated the last-mentioned experiment several times, with the utmost care; but I did not discover the smallest sign of exhaustion in the metal, notwithstanding the large quantities of heat actually given off.

Finding so much reason to conclude, that the heat generated in these experiments, or excited, as I would rather choose to express it, was not furnished at the expense of the latent heat or combined caloric of the metal, I pushed my inquiries a step farther, and endeavored to find out whether the air did, or did not, contribute any thing in the generation of it.

Experiment No. 2

As the bore of the cylinder was cylindrical, and as the iron bar, (m) to the end of which the blunt steel borer was fixed, was square, the air had free access to the inside of the bore, and even to the bottom of it, where the friction took place by which the heat was excited.

As neither the metallic chips produced in the ordinary course of the operation of boring brass cannon, nor the finer scaly particles produced in the last mentioned experiments by the friction of the blunt borer, showed any signs of calcination, I did not see how the air could possibly have been the cause of the heat that was produced; but, in an

investigation of this kind, I thought that no pains should be spared to clear away the rubbish, and leave the subject as naked and open to inspection as possible.

In order, by one decisive experiment, to determine whether the air of the atmosphere had any part, or not, in the generation of the heat, I contrived to repeat the experiment, under circumstances in which it was evidently impossible for it to produce any effect whatever. By means of a platen exactly fitted to the mouth of the bore of the cylinder, through the middle of which piston the square iron bar, to the end of which the blunt steel borer was fixed, passed in a square hole made perfectly air-tight, the access of the external air, to the inside of the bore of the cylinder, was effectually prevented. [In fig. 3. this piston (p) is seen in its place; it is likewise shown in fig. 7 and 8.]

I did not find, however, by this experiment, that the exclusion of the air diminished, in the smallest degree, the quantity of heat excited by the friction.

There still remained one doubt, which, though it appeared to me to be so slight as hardly to deserve any attention, I was however desirous to remove. The piston which closed the mouth of the bore of the cylinder, in order that it might be air-tight, was fitted into it with so much nicety, by means of its collars of leather, and pressed against it with so much force, that, notwithstanding its being oiled, it occasioned a considerable degree of friction, when the hollow cylinder was turned round its axis. Was not the heat produced, or at least some part of it, occasioned by this friction of the piston? and, as the external air had free access to the extremity of the bore, where it came in contact with the piston, is it not possible that this air may have had some share in the generation of the heat produced?

Experiment No. 3.

A quadrangular oblong deal box, [see fig. 4] water-tight, 11 $\frac{1}{2}$ English inches long, 9 $\frac{4}{10}$ inches wide, and 9 $\frac{6}{10}$ inches deep (measured in the clear) being provided, with holes or slits in the middle of each of its ends, just large enough to receive, the one, the square iron rod to the end of which the

blunt steel borer was fastened, the other, the small cylindrical neck which joined the hollow cylinder to the cannon; when this box (which was occasionally closed above, by a wooden cover or lid moving on hinges), was put into its place; that is to say, when, by means of the two vertical openings or slits in its two ends, (the upper parts of which openings were occasionally closed, by means of narrow pieces of wood sliding in vertical grooves), the box [g, b, j, k, fig. 3] was fixed to the machinery, in such a manner that its bottom [i, k] being in the plane of the horizon, its axis coincided with the axis of the hollow metallic cylinder; it is evident, from the description, that the hollow metallic cylinder would occupy the middle of the box, without touching it on either side [as it is represented in fig. 3], and that, on pouring water into the box, and filling it to the brim, the cylinder would be completely covered, and surrounded on every side, by that fluid. And further, as the box was held fast by the strong square iron rod, [m] which passed, in a square hole, in the centre of one of its ends, [a, fig. 4] while the round or cylindrical neck, which joined the hollow cylinder to the end of the cannon, could turn round freely on its axis in the round hole in the centre of the other end of it, it is evident that the machinery could be put in motion, without the least danger of forcing the box out of its place, throwing the water out of it, or deranging any part of the apparatus.

Everything being ready, I proceeded to make the experiment I had projected, in the following manner.

The hollow cylinder having been previously cleaned out, and the inside of its bore wiped with a clean towel till it was quite dry, the square iron bar, with the blunt steel borer fixed to the end of it, was put into its place; the mouth of the bore of the cylinder being closed at the same time, by means of the circular piston, through the centre of which the iron bar passed.

This being done, the box was put in its place, and the joinings of the iron rod, and of the neck of the cylinder, with the two ends of the box, having been made water-tight, by means of collars of oiled leather, the box was filled with cold water, (viz. at

the temperature of 60 degrees), and the machine was put in motion.

The result of this beautiful experiment was very striking, and the pleasure it afforded me amply repaid me for all the trouble I had had, in contriving and arranging the complicated machinery used in making it.

The cylinder, revolving at the rate of about 32 times in a minute, had been in motion but a short time, when I perceived, by putting my hand into the water, and touching the outside of the cylinder, that heat was generated; and it was not long before the water which surrounded the cylinder began to be sensibly warm.

At the end of 1 hour I found, by plunging a thermometer into the water in the box, (the quantity of which fluid amounted to 18.77 lb. avoirdupois, or 21¼ wine gallons), that its temperature had been raised no less than 47 degrees; being now 107 degrees of Fahrenheit's scale.

When 30 minutes more had elapsed, or 1 hour and 30 minutes after the machinery had been put in motion, the heat of the water in the box was 142 degrees.

At the end of 2 hours, reckoning from the beginning of the experiment, the temperature of the

water was found to be raised to 178 degrees.

At 2 hours 20 minutes it was at 200 degrees; and at 2 hours 30 minutes it actually boiled!

It would be difficult to describe the surprise and astonishment expressed in the countenances of the bystanders, on seeing so large a quantity of cold water heated, and actually made to boil, without any fire.

Though there was, in fact, nothing that could justly be considered as surprising in this event, yet I acknowledge fairly that it afforded me a degree of childish pleasure, which, were I ambitious of the reputation of a grave philosopher, I ought most certainly rather to hide than to discover.

The quantity of heat excited and accumulated in this experiment was very considerable; for, not only the water in the box, but also the box itself, (which weighed 151¼ lb) and the hollow metallic cylinder, and that part of the iron bar which, being situated within the cavity of the box, was immersed in the water, were heated 150 degrees of Fahrenheit's scale; viz. from 60 degrees (which was the temperature of the water, and of the machinery, at the beginning of the experiment), to 210 degrees, the heat of boiling water at Munich. □

History and Nature of Science

An Account of James Watt and the Steam Engine*A Plain Story*

W. found that a well-made brass model of Newcomen's engine, consumed quantities of steam and fuel out of all reasonable or direct proportion with larger engines. He consulted Desaguliers' "Natural Philosophy," and Belidor's "Architecture Hydraulique," the only books from which he could hope for information. He found that both of them reasoned learnedly, but by no means satisfactorily; and that Desaguliers had committed a very gross arithmetical error in calculating the bulk of steam from the water evaporated in a common steam-engine; which being rectified, it appeared next that his data, or assumed facts, were false. By a simple experiment, W. found what was the real bulk of water converted into steam; and from his friend Dr. Black he learned what was the heat absorbed and rendered latent by the conversion of water into steam, which the Doctor then publicly taught, and had done for some years. Experiments had been made long before by Dr. Cullen, Mr. John Robinson, and others, in public classes, which proved that water, when placed in an exhausted receiver, boiled, and was converted into steam at the heat of 70 degrees or 80 degrees of Fahrenheit's thermometer, while it was well known that under the pressure of the atmosphere it required 212 degrees of heat to make it boil, and emit steam capable of displacing the air. It was evident that under intermediate pressures, intermediate degrees

of heat would be required to make it boil, and that in the steam-engine more or less cold water must be thrown in according to the degree of exhaustion which might be required; or, in other words, according to the number of pounds per inch the engine was loaded to.

Newcomen's and Savery's engines existed; the latter were in general laid aside, on several accounts, but the principal one seems to have been that the cold water, the raising of which formed the effect of the engine, entered the steam-vessel itself, which in general was not a cylinder, but was of an oval or egg form; and, by cooling it, destroyed a great quantity of steam when it came next to be filled, which Desaguliers expressly notices. This engine, however, had an injection of cold water, to commence the condensation of steam, and Savery seems to have been the inventor of that valuable article; but he also seems in some cases to have condensed the steam by pouring cold water on the outside of his copper steam-vessel.

In Newcomen's engine the steam-vessel was a cylinder, or so meant to be. A piston was suspended, moveable in that cylinder; this piston hung by chains to the arch of a strong double-ended lever like a scale-beam, to the other end of which the rods which wrought the pumps were suspended in the like manner. The steam was admitted from a covered boiler, through a pipe, into the cylinder

below the piston; the air was blown out by the steam at a pipe near the bottom of the cylinder, called the snift. The passage from the boiler was shut; cold water was spouted or injected into the cylinder from a cistern placed higher; the steam was thus condensed or rendered less elastic, the other end or mouth of the cylinder being open; the pressure of the atmosphere, not being resisted by an equally elastic fluid within, or under the piston, weighed upon the latter and caused it to descend, which, by means of the lever, drew up the pump-rods and raised the water. The injection-cock or valve was then shut, the steam regulator or valve was opened, steam was readmitted, the equilibrium of pressure upon the upper

and under sides of the piston was restored, and the superior weight of the pump-rods, by means of the great lever or working beam, drew the piston to the top of the cylinder, and the operation recommended. When the piston was at the bottom of the cylinder, the air which entered with the steam and with the injection water was blown out at the snift, and the hot water left in the cylinder was expelled through another pipe, called the eduction-pipe, which proceeded from the bottom of the cylinder, several feet downwards, and its lower end stood in a cistern of water, and was furnished with a valve to prevent regress.

The steam-valve and the injection-cock were opened and shut by certain mechanism called working gear, which was put in motion by means of pegs in a piece of wood which was hung to and moved with the working beam, and was called the plug-tree.

In order to supply the engine with cold water, it wrought a pump called a jack-head pump, which was shut at top by an iron cover, and its pump-rod wrought through a collar of oakum, which permitted the rod to slide up and down while it precluded the exit of the water, which was raised to a greater height through a side branch turned upwards.

Thus the latent heat of steam was discovered and published by Dr. Black—the boiling of water in vacuo at low degrees of heat, was discovered and published by Dr. Cullen, Mr. Robinson, and several others.

The elastic powers of steam were known to Hero of Alexandria, and to many ancient writers. The steam-engine was invented by the Marquis of Worcester, Savery, Papin, and Newcomen.

The means of confining steam, and the making valves, cocks, and regulators, were known to all of them. Pumps for drawing both air and water out of vessels or reservoirs were well known to everybody. An Air-pump, with a piston-rod moving through a collar, was invented and published by Mr. Smeaton; and the same method, even before him, was commonly used in the jack-head pumps of common steam-engines and in other machines:— (this relates to the piston-rod of the cylinder; for in respect to the air-pump it is not necessary, though convenient, that it be shut at top.)

A cylinder and moveable piston were used in Newcomen's engine; so were the working beam and working gear, or machinery for opening and shutting the valves and cocks.

The steam was condensed by a spout of cold water in Savery's and in Newcomen's engines; and, as it is said in Desaguliers, cold water was poured on the outside of the steamvessels for the same purpose. Everybody knew that cold bodies of all kinds condensed steam when they came in contact with it. There were pipes in all those engines which admitted the steam from the boiler, and cocks or valves which shut it out from that vessel; and in Newcomen's engine there was a pipe which conveyed away the hot water, and a valve which prevented its regress.

The diameters of those pipes, which admitted the steam and let out the injection water, had been ascertained sufficiently near. The size and form of boilers, which answered sufficiently well, had also been ascertained.

Of all those things, Watt must say, “Non ea nostra voco.” The things that are his remain to be told.

He found, by the application of the knowledge which has been mentioned, that the cause of the great consumption of fuel was, that the cylinder being cooled by the injection-water, that vessel must condense a large quantity of steam whenever it was attempted to be again filled with steam; that

the vacuum could not approach to perfection without the steam was cooled below 100 degrees; and that such cooling would increase the evil complained of in a four-fold or greater ratio, because the penetration of that heat or cold into the cylinder would be as the squares of the differences of the heats between that vessel and the steam. How was this to be avoided?

He tried to make the cylinders of wood or other materials which conduct heat slowly, but he could not prevent the steam from coming into contact with the comparatively cold water which remained in the bottom of the cylinder, and which must be expelled by the steam; besides, his wooden cylinders did not seem likely to be of long duration. In such-like experiments he spent much time, and more money than was suitable to his circumstances, yet he made no advances towards a beneficial discovery. But the matter having got firm hold of his mind, and his circumstances obliging him to make exertions to regain what he had spent, he turned the matter over in every shape, and laid it down as an axiom—that to make a perfect steam engine, it was necessary that the cylinder should be always as hot as the steam which entered it, and that the steam should be cooled down below 100 degrees in order to exert its full powers. The gain by such construction would be double—first, no steam would be condensed on entering the cylinder; and secondly, the power exerted would be greater as the steam was more cooled. The postulata, however, seemed to him incompatible, and he continued to grope in the dark, misled by many an ignis fatuus, till he considered that steam being an elastic fluid, it must follow the law of its kind; and that if there were two vessels, A and B, of equal or other dimensions, the one, A, filled with steam, and the other, B, exhausted, if a communication were opened between those vessels, the steam would rush from the full one into the empty one, and they would both remain half exhausted (if the vessels were equal in size), or be filled with steam of half the density. If, then, into the second vessel, B, an injection of cold water were made, or cold water applied to its outside in sufficient quantity, the portion of steam which it contained would be

condensed or reduced to water; and by the same law of nature that had operated before, more steam would issue from A into B until the whole was condensed, and nearly a perfect vacuum established in both vessels; yet as the cold water had not entered or touched A, that vessel would still retain its heat.

This idea once started, the rest immediately occurred. The vessel A being supposed to be the cylinder, B would be the vessel called now the condenser; the water, air, & c., accumulated in B, he immediately saw could be discharged or drawn out by means of a pump, or the water might be let run out by a pipe more than 34 feet long going downwards, and the air might in that case be expelled at a valve by filling B with water, provided the descending eduction-pipe were shut meanwhile. On the whole, however, he preferred the pump. Another difficulty appeared, which was the making the piston tight. That could not be done with water, as in Newcomen's engines; for that might get in and evaporate, and produce steam. He therefore thought of wax, oil, and similar substances, as substitutes, knowing that they would not evaporate in the heat of boiling water; and, for greater security, he proposed to employ the steam itself as the acting power on the piston.

The diameters of the pipes necessary to convey the steam into and out of the cylinder, he regulated from those in use. The size of the condenser he assumed at random, as he did that of the air-pump, which it was evident must be larger than was necessary to contain the water and probable quantity of air. All this passed in his mind in the course of a few hours; and in a few days he had a model at work, with an inverted cylinder, which answered his expectations, and was, as far as he remembers, equal in its properties of saving steam and fuel to any he has made since, though in point of mechanism much inferior. Very simple cocks were employed as regulators or steam-valves, and his air-pump and condenser were of tin-plate. His cylinder, however, was good, and of brass, (about) 2 inches diameter and a foot long; the cocks were turned by hand instead of being wrought by the engine.

If Mr. W. Is thought worthy of credit in this matter, and the facts are consequently allowed, where was the might difficulty of putting the invention in execution from still fewer data than he has set forth in his specification? He is not so presumptuous as to think that there were not, and are not, numbers of mechanics in this nation, who, from the same or even fewer hints, would have completed a better engine than he did. Mr. Bramah has proved³ that he could, and W. Is inclined to believe him. But W. Does not pretend that any body could have done it without thinking upon it, nor without much previous knowledge and some experience of similar things.

Had W. been content with the mechanism of steam-engines as they then stood, his machine might soon have been brought before the public; but his mind ran upon making engines cheap as well as good: and he had a great hankering after inverted cylinders and other modifications of his invention, which his want of experience in the practice of mechanics in great, flattered him would prove more commodious than his matured experience has shown them to be. He tried, therefore, too many fruitless experiments on such variations. He wanted experience in the construction of large machines; that he endeavored to acquire; but experimental knowledge is of slow growth, and with all his ingenuity, so much boasted to his prejudice, he was concerned in making some very indifferent common engines. Other avocations, to him necessary, obliged him to turn his attention from the subject till he obtained the patent, so that at that time he had made no advances in the improvement of the mechanism. He therefore thought it proper to specify only what was his invention, and to leave any mechanical improvements he might make to be secured by other patents, if worthy of them.

His idea, then, was to apply his invention to the steam-engines as they existed. For this purpose there

was nothing else necessary than to shut up the snift, to apply a regulator or valve to the opening of the eduction-pipe within the cylinder, an air-pump to the outer end of that pipe, and to inject into the upper end of the eduction-pipe. If, at the same time, the cylinder was defended from the cold of the atmosphere, the engine would thus be complete, if the weight of the atmosphere were to be employed as the acting power; for all the regulators could be easily opened and shut by the then existing contrivances, and the air-pump rod could be suspended from the working beam.

If, however, the engine was wanted to receive all the advantages of the invention, the cylinder was to be placed in a case containing steam, with access for that fluid to the upper side of the piston, so that it might act upon it as the atmosphere acted in common engines, or in the case just stated. And in this latter manner were the engines made which he constructed in the beginning of the business; that is to say, the cylinders were fixed in a case containing steam, with which fluid they were wholly surrounded; and, their mouths being open within the case, the steam had always access to the upper side of the piston, and was admitted to the part below the piston only when the piston was rising. The opening from the cylinder into the eduction-pipe was shut by a valve while the piston was rising, but when it was required to descend, that valve was opened. Those valves were of the sliding kind used in Newcomen's engines. The injection was made into the eduction-pipe; and the air-pumps, which drew out the water as well as the air, were fixed to the bottom of the eduction-pipe, which had a valve to prevent regress as usual.

There was sometimes one pump, and sometimes there were two or three, as circumstances or the fancy of the moment directed. The working beams and working gear were made in the usual manner, or nearly so; and in cases where there were boilers fixed for the common engine, which was superseded, they were used without alteration. ■

3. i.e., Given it in evidence.