

crease with the time x , we obtain the series $1, 1x, 2x^2, 3x^3$, etc., wherein appears the leading numerical factor concerned in the process of differentiation: or if the unit of operation be negative, the series becomes $1, -1x, +2x^2, -3x^3, +$ etc., corresponding to the differentials of a negative function: and finally when the unit of operation is circulative, we enter upon the differentiation of exponential functions. Nature, in the case of a body falling in a vacuum under the influence of the force of gravitation, actually develops the function $(x+h)^2$; and it is the intention of the Calculus of Operations to exhibit the harmony which subsists between the objective and subjective, between the phenomena of the external world, and the mental processes which investigate and record them.

ART. XXXVI.—*On the Mammoth Cave of Kentucky*; by Prof. B. SILLIMAN, Jr. (From a letter addressed to Prof. Guyot, Cambridge; dated Louisville, November 8, 1850.*)

I HAVE lately had an opportunity of visiting the Mammoth Cave of Kentucky and have made in connection with Mr. R. N. Mantell a collection of the animals found there, which we propose to send to our much valued friend, Prof. Agassiz, by an early opportunity. My object in writing to you is to say a word regarding the general topographical features of the country and some other matters which I suppose will interest you.

At the level of the Ohio below the falls on which the city stands, are found the lower beds of silurian rocks and upper Devonian, the oldest palæozoic rocks to be seen in all this region. This city is placed on a plateau elevated some seventy-five feet above the low-water mark of the Ohio, and the plain on which it stands represents the general level of the surrounding country for a long distance above and below. Mammoth Cave lies in a direction nearly south of Louisville on the Green river and on the direct road to Nashville, midway between Louisville and the latter city. Leaving Louisville, the stage road follows the main course of the Ohio and generally along its banks to the Salt river, some twenty miles; crossing this river the road bears south, leaving the Ohio on the right, and soon enters a new region. By a gentle and easy ascent you continue to rise for several miles by a circuitous path, passing in succession all the members of the si-

[* The following letter was written with no intention of its being published and only for the gratification of a friend, who has since urged its publication. It is therefore given exactly as it was first written, which may, I trust, be deemed a sufficient apology for whatever want of fullness of detail attaches to a general and rapid sketch.—B. S., Jr.]

lurian and the lower secondary or the mountain limestone until at an elevation of 300 to 400 feet above the Ohio you reach the great upper plateau which stretches away for a long distance, interrupted only by the deep river beds, which are all very nearly on the same level with the Ohio. These upper plains are called the '*Barrens*,' from the general sterility of the soil, which is formed to a considerable extent of stiff red clays and unproductive sands, or of lime rocks lying near the surface. Everywhere in this upper country we are struck with the frequent occurrence of those circular holes or shallow pans which are called 'sinks,' from the popular belief that the surface has fallen away or sunk at some recent period. You see large trees standing dead in the water which fills these hollows, in a situation where of course they could not have grown supposing the water had long occupied its present place. Hence the idea so generally accepted that the surface of the earth has fallen downward, and this is attributed to the wearing away of the rocks beneath by subterranean rivers or by some other mode of aqueous action. It is probable that the hollows, already existing, are made water-tight by the cementing of the surface by fine mud floated by rains from the adjacent roads. I saw hollows of this sort standing full of water in this very dry season, in which the trees were not quite dead, while in others only the denuded trunks were seen. From these stagnant pools arise the poisonous miasms that produce the fevers which are peculiarly abundant in those parts of the Barrens where the sinks are most numerous. It is remarked that the 'sinks' have greatly increased in number, and the miasms in virulence, since the country was opened by cultivation and by roads. These causes have obviously operated to furnish the slime which the rains have washed down into the circular hollows adjacent these improvements, thus rendering them water-tight.

The stage-road to Nashville runs over this upper plateau all the way from Salt river with unimportant exceptions in the valleys of small rivers, until it reaches the valley of the Cumberland river, over one hundred and fifty miles. Within some ten or fifteen miles of Nashville the traveller again descends by a similar gradual declivity full 350 feet to the banks of the Cumberland river, on which the city of Nashville stands. Here again the observer detects the oldest silurian rocks, compact blue crystalline limestones in which the fossils are almost obsolete, and unfossiliferous sandstones, alternating with them.

The Mammoth Cave of Kentucky is situated in the midst of the great upper plain and descends from the uppermost rocks to those which are nearly or quite on a level with the Ohio. Dr. John Locke of Cincinnati has measured the depth of the cave barometrically, and is said to have determined it to be 325 feet

below the hotel, and the level of the rivers of the cave to be the same as that of Green river with which the subterranean rivers or lakes rise and fall in times of flood; so that there is no doubt of a connection existing between Green river and these curious subterranean pools over which the explorer passes in mysterious silence many miles from the entrance, and at least 300 feet from the upper surface. Unfortunately our party was unprovided with barometers, and the measurement of Dr. Locke remains therefore as the only evidence we have of the relative levels of these subterranean waters and Green river.

One atmospheric phenomenon attracted our attention and tasked our ingenuity for a satisfactory explanation. I will mention the fact and our solution of it. If the external air has a temperature above 60° F., the observer, on approaching the mouth of the cave, is met by a blast of cool air blowing outward from the mouth; and if the external temperature is high, say 90° F., the blast amounts to a gale. It is almost impossible, indeed, where the difference of temperature, either way, is considerable, to make the entrance of the cave with a lighted lamp; unless carried with an experienced hand it is surely extinguished. In hot weather, this contrast of temperature and its accompanying blast of air, are at first quite overpowering and you feel as if immersed in a cold bath.

If the air without has a temperature of 59° – 60° no current is observed and the flame of a lamp held in a favorable position indicates none. It immediately occurred to me that there must be two currents, one above of warmer air, passing inward, and one below of colder air passing outward, and the reverse, but experiment soon satisfied me that this was not the case. Only one current could be discovered, and on inquiry of the very intelligent guide, 'Stephen,' who is well known for his remarkable powers to all who have been at the cave, I found that this phenomenon had attracted his attention, and that he was satisfied from many observations that only one current existed and that this flowed *out* when the external air was above 60° and *inward* when this was below 60° . Going in, one day at noon, we found the outward blast very strong: we prolonged our stay until past midnight; meanwhile a storm of rain accompanied by lightning had come up, and at 3 A. M. when we again emerged, the temperature outside had fallen to 50° , and the inward gale blew so strongly as to extinguish our lights several hundred yards from the mouth. In fact the guide told us, when more than two miles in the cave, that a change had taken place in the outer air, and that we should probably find a storm raging without. His accustomed senses detected the gentle current inward which we did not notice at so great a distance, and he perceived, as he afterward told us, a change of level in the subterranean rivers since

our crossing them in the morning—the rain which had fallen copiously having already affected them.

I was at a loss for a little time to account for these currents of air, but the following explanation suggested itself. The mouth of the cave is the only communication between the external air and the vast labyrinth of galleries and avenues which stretch away for many miles in the solid limestone. The extent of these underground valleys of denudation, or rather 'excavations,' is vastly greater than I had imagined before going there; branching, crossing, inosculating in all directions, and at all levels, the mind is lost in amazement at their vast proportions, the various beauty which they possess, and at the continuity of the cause which has formed them. The air which they contain is pure and exhilarating. The nitre beds which are of incredible extent in these galleries probably account in part for the purity of the air, as the nitrogen which is consumed in the formation of the nitrate of lime must have its proportion of free oxygen disengaged, thus enriching this subterranean atmosphere with a larger portion of the exhilarating principle. The temperature of the cave is uniformly 59° F., summer and winter, and this is probably very near to the annual mean of the external air. The expansion which accompanies an elevation of temperature in the outer air is immediately felt by the denser air of the cave, and it flows out in obedience to the law of motion in fluids, and the outward current continues without interruption as long as the outer air is possessed of a higher temperature than the cave.

I was assured by those resident on the spot, that for weeks or even months, in the summer and winter, this blast of air continues with unabated force outward or inward, and yet the thermometer at a distance from the mouth always indicates the same temperature. This seems to me of itself a very convincing proof of the vast volume of the subterranean galleries; for otherwise the equilibrium being soon restored, the current would cease, or the temperature within would vary. Still it must be regarded as an interesting place for a series of observations with the barometer and thermometer continued daily for a year, and it would not be difficult to arrange such a series, if the question was esteemed to possess sufficient scientific interest to warrant the expense. If the cave had two openings at different levels, the temperature would not be uniform and there would be two currents discernible.

There is no exception to the purity of the air in the Mammoth Cave, in none of the deep pits or domes is it possible to find any accumulation of carbonic acid or other noxious gases, respiration and combustion are perfect in all parts which have yet been visited. The waters of the springs and rivers within it are all limpid and potable, and the avenues with few exceptions are dry at all seasons. I thought it very remarkable that in all its vast extent

there should be no sources of sulphuretted hydrogen and of carbonic acid.*

The phenomena of life within the cave are comparatively few but interesting. There are several insects, the largest of which is a sort of cricket with enormously long antennæ. Of this insect, numerous specimens will be found among the specimens sent to Prof. Agassiz. There are several species of Colcoptera, mostly burrowing in the nitre earth. There are some small water-insects also which I suppose are Crustacean. Unfortunately three vials containing numerous specimens of these insects were lost with my valise from the stage coach, and I fear will not be recovered. Of the fish, there are two species, one of which has been described by Dr. Wyman in the American Journal of Science, and which is entirely eyeless;† some ten or twelve specimens of the species were obtained. The second species of fish is not colorless like the first, and it has external eyes, which however are found to be quite blind.‡ The craw-fish or small crustacea inhabiting the rivers with the fish are also eyeless and uncolored, but the larger-eyed and colored craw-fish which are abundant without the cave, are also common at some seasons in the subterranean rivers, and so also it is said the fish of Green river are to be found in times of flood in the rivers of the cave. Among the collections are some of the larger-eyed craw-fish which were caught by us in the cave. The only mammal except the bats, observed in the cave, is a rat which is very abundant, judging from the tracks which they make, but so shy and secluded in their habits that they are seldom seen. We caught two of them, and fortunately male and female.

The chief points of difference from the common rat in external characters, are in the color, which is bluish, the feet and belly and throat white, the coat which is of soft *fur* and the tail also thinly furred, while the common or Norway rat is gray or brown, and covered with rough hair. The cave rat is possessed of dark black eyes, of the size of a rabbit's eye and entirely without iris; the feelers also are uncommonly long. We have satisfied ourselves that he is entirely blind when first caught, although his eyes are so large and lustrous. By keeping them however in captivity and diffuse light they gradually appeared to attain some power of vision. They feed on apples and bread, but will not at present touch animal food. There is no evidence that the cave rats ever visit the upper air, and there was no one who could tell me whether they were or were not found there by the persons who first entered this place in 1802.

* Near "Mary's Bower" there is a spring of bitter water evidently containing sulphate of magnesia, which salt is also found abundantly in some parts of the cave.

† See also Proceedings Bost. Soc. Nat. Hist., 1850, 349.

‡ For a list of the animals found in the cave as mentioned by Prof. Agassiz, see this volume, page 127.

Bats are numerous in the avenues within a mile or two of the mouth of the cave, and Mr. Mantell thinks he has secured at least two species. Several specimens are preserved in alcohol. It was not yet quite late enough in the season when we were at the cave, Oct. 16th-22d, for all the bats to be in winter quarters, as the season was very open and warm. Still in the galleries where they most abound, we found countless groups of them on the ceilings chipping and scolding for a foothold among each other. On one little patch of not over four by five inches, we counted forty bats, and were satisfied that one hundred and twenty at least were able to stand on a surface a foot square; for miles they are found in patches of various sizes, and a cursory glance satisfied us that it is quite safe to estimate them by millions. In these gloomy and silent regions where there is neither change of temperature nor difference of light to warn them of the revolving seasons, how do they know when to seek again the outer air when the winter is over and their long sleep is ended? Surely he who made them has not left them without a law for the government of their lives.

You may enquire what has formed the excavations of Mammoth Cave. I answer clearly and decidedly *water* and no other cause. No where else can we find such beautiful sculptured rocks as in Mammoth Cave; such *perfect* unequivocal and abundant proofs of the action of running water in corroding a soluble rock. The rough hewn block in the quarry, does not bear more distinct proof of the hammer and the chisel of the workman, than do the galleries of Mammoth Cave of the denuding and dissolving power of running water. At Niagara we see a vast chasm evidently cut by water for seven miles, and still in progress, but we cannot see beneath the cataract the water-worn surfaces, nor the rounded angles of the precipice—while the frosts and rains of countless winters, have reduced the walls of the chasm itself to a talus of crumbling and moss-grown rocks. But in the Mammoth Cave we see a freshness and perfection of surface, such as can be found only where the destructive agencies of meteoric causes are wholly absent, aided and quickened as those are on the upper surface by the processes of vegetable life, wholly unknown in the cave. Here we have the dry beds of subterranean rivers, exactly as they were left thousands of years ago by the stream which flowed through them when Niagara was young. No angle is less sharp, no groove or excavation less perfect than it was originally left, when the waters were suddenly drained off by cutting their way to some lower level. The very sand and rounded pebbles which pave the galleries now and formed the bed of the stream of old, have remained in many of the more distant galleries untrodden even by the foot of man. The rush of ideas

was strange and overpowering as I stood in one of these before unvisited avenues, in which the glow of a lamp had never before shone, and considered the complex chain of phenomenon which were before me. There were the delicate silicious forms of cyathophylla and encrinites, protruding from the softer limestone which had yielded to the dissolving power of the water; these carried me back to that vast and desolate ocean in which they flourished and were entombed as the crystalline matrix was slowly cast around them, mute chroniclers of a distant epoch. Then there were the long succeeding epochs of the upper secondary, and these past, the slow but resistless force of the contracting sphere elevated and drained the rocky beds of the ancient ocean: the action of meteorological causes commenced and the dissolving power of fresh water, following the almost invisible lines of structure in the rocks, began to hollow out these winding paths, slowly and yet surely. But I need not attempt to paint a picture in detail whose outlines in simple truth are so grand, and I must apologise for detaining you so long. I wish that all my scientific friends could visit the Mammoth Cave; it teaches many lessons in a manner not to be learned so well elsewhere, and in this respect I was most agreeably disappointed. I had heard that its interest was chiefly scenic; but I found it to exceed my utmost expectations as well in its illustrations of geological truth, as in the wonderful character of its features. I will not detain you with any attempts at descriptions of single parts, as no description can awaken those peculiar and deep emotions, which a personal study of its details is calculated to produce.

I know not how or where to stop, however, in my account of this interesting place. Excuse me if I trespass yet a little longer on your patience. In traversing the high vaulted galleries of the cave, our attention was occasionally arrested by the sound of falling water. We soon learned that in such cases we were in the vicinity of an entirely new feature in this subterranean region. Approaching cautiously to the spot from which the sound proceeds, we find usually a deep pit often surmounted by a dome. These pits are of various depths, but usually not less than one hundred feet, and cut down with walls of limestone so entirely vertical, that in many cases we were able to measure them from the edge with a line and plummet. When the gallery leads to the upper portion of one of these vertical excavations, it is called a *pit*; if on the other hand the approach is from beneath, it is usually called a *dome*, from the regular and arched appearance of the ceiling. These pits or domes are sometimes of almost incredible height, and I am satisfied that in one or two instances, they reach through the entire vertical thickness of all the strata composing the cave, or near three hundred feet. Such is Gorin's dome, one of the most remarkable features of the cave. Without seeing them you will

hardly credit and cannot appreciate the sharpness with which the vertical walls of this pit are moulded into architectural forms. At one point the outer diameter of the circle bounding it comes so close to one of the adjacent galleries, that the thin shell of interposed rock has been removed for a space two feet square through which as through a window, the observer may put his head and obtain an imperfect glimpse of the interior. You perceive that the loop-hole through which you look is midway between the ceiling and the first gallery below, and by a Bengal-light or other powerful illumination, a tolerable view is obtained of the vast proportions of this monolithic structure, built without hands. I was provided with the means of producing the Drummond light, and with the guide, my assistant and Mr. Mantell, we succeeded in making the perilous descent (where only by groping in the dark over profound chasms could we find a foothold) to a point some hundred feet below the opening above described. Here we erected the Drummond light, and by its aid obtained the first view of its lofty ceiling. The dome is of an irregular outline, in the main ovoidal, and from the ceiling hangs a great curtain of sculptured and vertically-grooved rock unsupported below, with the graceful outline and apparent lightness of actual drapery. A small stream of water falls from the top, which is broken into spray long before it reaches the bottom, and keeps the whole interior wet with its splashing. No gallery has been found which leads to the bottom of this most beautiful dome. We found other similar domes in which the pendant curtain just described had fallen, and portions of it but little removed from their original position, seemed poised to a second fall.

Of the mysterious rivers, with their many-tongued echoes—the mounds of mud and drift which they annually heap up,—the long miles of avenues which stretch away beyond them, rugged or smooth,—and of the vaulted ceilings, crystal grottos and gypsum coronets which tempt the mineralogist to untiring exploration, I must say nothing, for I have already gone too far in trespassing so much upon your kindness.