Essay

Is Gravity a Fundamental Force?

Jonathan J. Dickau*

Abstract

When a stone falls to the Earth, there is no doubt its falling reveals a force we must all live with – throughout our lives. And yet, there is a debate among scientists as to whether gravity is a fundamental force of the universe or not. We know there is a hierarchy among the forces, but typically assume there is an anomaly with gravity – because it is the weakest force, yet thought to have split from the unified force in the early universe. The work of Jacobson, Verlinde, Padmanabhan, and others, suggests we should instead see gravity as a consequence of the remaining forces – rather than a fundamental force – and this view gives unique insights into possible quantum gravity theories and the nature of gravity itself. What if gravity is different because it comes mainly from asymmetry instead of symmetry? This paper explores relationships between entropic or dissipative forces and gravitation, in regards to whether gravity is indeed a fundamental force in Physics, is a residual or consequence of other forces that *are* fundamental, or if all forces are the consequence of just one unified field of interactions – and sub-ranges thereof. The author's prior work involving the Mandelbrot Set and Physics analogues suggests this third case is the correct answer.

Keywords: Entropic gravity, emergent gravity, induced gravity, Mandelbrot Set.

Introduction

Determining what is fundamental in Physics, and what is derivative, has long been a subject of debate among physicists, mathematicians, and philosophers. To have a meaningful understanding of the fundamentals of Physics requires considerable learning and understanding, just to get the basics right. Correctly understanding more than the basics requires years of study in some fields, and quite a lot more if you hope to master the skills needed to duplicate the feats of those who went before, or better still to exceed their insights. I learned, in first year College Physics, from a book entitled "Fundamentals of Physics" by Halliday and Resnick [1] which led me to discover some essential elements, and gave me an idea of what is fundamental to our knowledge. I mainly wanted to obtain a better understanding of how things work in the real world, through a grasp of essential knowledge in the physical sciences.

However it quickly became clear that this pursuit is part of the larger search for knowledge and the progress of humans' understanding or knowledge of the universe, and how it works. This sounded very exciting. We were taught that learning how to learn about the universe is a worthy

* Correspondence: Jonathan J. Dickau, Independent Researcher. E-mail: jonathan@jonathandickau.com

goal, for its own sake, and since then I have seen that this lesson fueled the pursuits of many scientists – including Nobel laureates – who made great discoveries. So perhaps the one fundamental thing in Physics is the search for and progression of knowledge. But there are questions about what is at the root of all, which deserve clear answers.

I was taught in College that gravity is one of the four fundamental forces, along with the electromagnetic, weak-nuclear, and strong-nuclear force. However; work on the frontiers of theoretical Physics sometime redefines what is fundamental in nature, and how forms and forces are derived from more basic or general principles of which they are a subset and example, or from which they emerge. Understanding these relationships is what gives us the power to craft unifying theories, such as a GUT or TOE. One promising avenue for unification is the idea that gravity is a consequence of the other forces and entropy, rather than a fundamental force of Physics, in its own right.

A paper by Jacobson [2], another from Verlinde [3], and work by Padmanabhan [4], set the stage for a redefinition of gravitation along these lines. But there may be a deeper underlying cause for entropic gravity, and indeed for the 2^{nd} law of thermodynamics, which is fundamental asymmetry. While others have sought an understanding of Physics from the symmetry groups; I have been learning things from the Mandelbrot Set that also teach lessons about Physics, and may shed more light on gravity than on other subjects – in view of the work cited above – because it is the embodiment of asymmetry, and a catalog of symmetry-breaking structures [5]. A key to understanding this is that structures in $\mathcal{M}$ balance local symmetry with global asymmetry, so near-perfect symmetry is observed at high magnification – for many locations – while the same structure is observed to be asymmetrical at lower magnification [6].

Of course, there is a profound realization to the idea that the laws of Physics are shaped as much by asymmetry as by symmetry, but this view is reflected in theories of gravitation where gravity is seen as emergent, entropic, or thermodynamic. However; the notion that asymmetry is as fundamental to Physics as symmetry takes some getting used to. We were taught Emmy Noether's discovery [7] that all conservation laws are determined by an accompanying symmetry*, and this remains true despite any reasons why asymmetry is also a part of our reality. So I am not suggesting we need to abandon our focus on symmetry and conservation laws, but the other side of the coin needs to be carefully examined, and it needs to be acknowledged that both sides of the coin are important.

If we see symmetry-breaking and asymmetry are as important as symmetry, then we can explain thermodynamic entropy and see why quantum non-locality arises, easily. I have long advocated the idea that entropy can be characterized by the action of spreading and sharing as suggested by Leff [8], and advocated by Lambert [9], which is easily extended into the realm of what is now called quantum thermodynamics [10]. The crucial element is to include quantum information, along with the spreading and sharing of energy, such that both energy and information are seen as being shared and spread among the available spaces and states.

The description now favored by physicists goes like this. An atom or particle in any specific quantum state becomes entangled with others, whenever they interact, such that; over time the quantum information associated with a single entity becomes spread over several quanta and then many. In this way; information once localized is observed to spread out over time. This view characterizes recent attempts to combine quantum information theory and thermodynamics [11]. It was also expressed in the 1988 Doctoral thesis of Seth Lloyd [12]. Over time; information associated with any one particle is shared through coherent states with others, until the information no longer resides in the individual particle but only in the collective.

Using the terms of decoherence theory; localized components of the wavefunction are seen to spread over a larger ensemble of states, and then to merge or blend into the global wavefunction. I presented ideas at FFP10, in 2009, which reflect this sensibility, asserting a common basis for thermodynamic entropy and quantum non-locality [13]. In November of 2017; I gave a talk at FFP15, focusing on emergent, thermodynamic, and entropic theories of gravitation [14], that included material I presented at GR21, in July of 2016 – which explored connections between entropic gravity and the Mandelbrot Set [15]. Analogies can be made, linking Bose-Einstein condensation, Schwarzschild event horizons, and a specific Misiurewicz point in $\mathcal{M}$, that connect recent work by Dvali and colleagues [16] with my own research on the Mandelbrot Set and Physics [17] spanning over 30 years [18]. The remainder of this paper discusses how the work cited above can help us determine whether gravity is a fundamental force, or not.

Entropic Gravity and Asymmetry

The insight of Ted Jacobson, when he wrote on the "Thermodynamics of Spacetime" in 1995, was that gravitation in the spirit of Einstein could be viewed as a product or subset of thermodynamics, and thus derived from thermodynamic principles. This upsets the idea that gravity is a fundamental force, or that gravity derives solely from the bending and curvature of space. It got the attention of the Physics community though, and got people thinking about the possibility that there is another way to get to the same fundamental laws, without adhering to the conventional framework or mindset. Andrei Sakharov had suggested something similar back in 1967 [19], but Jacobson's paper set the stage to convince people that we can view the action of gravity as a residual of other forces, instead of a fundamental force of nature.

Later work by Verlinde had still greater impact, and Padmanabhan and numerous others [20], convinced a still larger segment of the Physics community that gravity is not a fundamental force after all, and is instead a consequence of the action of other forces, or an emergent effect of their collective action. Not everyone thinks this is reasonable. Objections have surfaced [21] suggesting these ideas cannot be true, or need to be modified to fit experimental or cosmological observations, but despite this; the status gravity had enjoyed as a fundamental force is significantly diminished. However; this prior status might be restored, if asymmetry is seen as a fundamental component of natural law.

It is fairly well-known in the Physics community that the Standard Model can be encoded in the symmetry group formula SU(3) × SU(2) × U(1), but it is not understood how to derive this formula from a deeper underlying structure. There are objects in Mathematics possessing deep and great symmetry, which are already known to be relevant to Physics and are obvious candidates for the seed of a unifying theory. E_8 was such a choice for Garrett Lisi's "Exceptionally Simple Theory of Everything," [22] given that it had already shown up as a key element of String Theory. But this model was later shown [23] to be a bit too simple a generalization to capture all the nuances of natural law.

It may be the case that no theory based on symmetry alone can capture the richness of nature, and if so; this is why theories of thermodynamic or entropic gravity tell us something we didn't know already. If the universe and natural law display a fundamental asymmetry it shows up in non-linear elements of form, and explains the 2nd law of thermodynamics. If the universe continues to expand and cool; this is evidence that Cosmology is inherently asymmetrical, because the cosmos is open-ended thermodynamically and thus far from equilibrium. However; the natural laws and their manner of emergence may be seen to arise similarly. Indeed; we have known for a long time that our cosmological pre-history is what gave rise to the natural forces in the form we now see them. But there is no clear consensus, in the Physics community, on a model which unifies the fundamental forces *and* explains cosmology.

Asymmetry, Entropy, and Mandelbrot Set Physics

What part do asymmetry and entropy play in the evolution of the cosmos? The Big Bang or Inflationary Universe involves a gross asymmetry between the early universe and the present, and continuation of the universe's expansion in the foreseeable future. As the early universe expanded, it cooled from being unimaginably hot to having the range of temperature we now enjoy. Along the way; we saw the creation of space give way to the production of particles, and then to nucleosynthesis, while the universe was still an energy soup – where matter and energy are interchangeable and ever interchanging, because the mean interaction distance is so small. This made it very inhospitable indeed. Before decoupling; no particle or photon could travel far without bumping into another, so there was a lot of particle annihilation and creation – and stable forms could not emerge. But the Dark Age after decoupling wasn't hospitable for living beings to survive either. So we can be glad things came together in a way it makes that possible here and now.

In a way; we can thank entropy for making life possible, since it assured that eventually the cosmos would cool enough for things to condense and congeal. But Carroll and Chen proposed [24] that entropy can account for Inflation as well, so long as we allow a Janus-like arrow of time. Since this is consistent with the hypothesis that asymmetry is a driver of cosmic evolution, and because I'd already learned a similar lesson from $\mathcal{M}$; I have continued to research this angle.

The notion the evolution of the cosmos might be encoded in the Mandelbrot Set came to me more than 30 years ago, when I first saw the silhouette of the Mandelbrot Butterfly figure on the screen of a friend's computer after he altered the code to blacken points where the iterand magnitude is successively diminishing. The Astrophysics course I was taking at College, which had just covered Big Bang Cosmology, set the stage in a very timely way for this insight. But it is easy to notice that $\mathcal{M}$ is grossly asymmetrical along the real axis, and it is well-known to be the most complex mathematical object of its kind.

So it should come as no surprise that $\mathcal{M}$ encodes the pattern by which the cosmos and the natural forces arise, once one learns that symmetry-breaking has an importance equal to symmetry-preserving relations in Physics. Moreover, if the cosmos and forces display fundamental asymmetry; one would expect gravity to arise as a residual – rather than a fundamental force – and to some extent the other forces should as well, since they all spring from one unified force. Papers have appeared supporting the idea that both the EM force [25] and also the nuclear forces [26] can be seen to arise via a mechanism similar to entropic gravity. So there are attempts to extend this analogy into a more general way to see the evolution of the natural forces and to derive them all using the same principles. This points the way toward unification of Physics by regarding asymmetry as a fundamental property of physical systems.

Part of the reason why this notion is not more obvious must be the way essential subjects are taught, once a sufficient level is reached to introduce more advanced topics, because the emphasis is different in Math and Physics courses, and both the treatment and terminology differs. In Physics; we typically emphasize a subset of equations that have a high degree of symmetry and/or other constraints, such that they are easily solvable once the appropriate formula is known.

While in Mathematics; there is clearly an emphasis on more general cases, and on a range of possible solutions, where the subset used in Physics is treated in passing and no understanding is imparted of why it is a special case. Instead, students simply learn to re-cast and re-focus when going from Math to Physics courses, without really understanding why. This hides the beauty of the interplay between symmetry and asymmetry, which could or should be a source of excitement for students, rather than a mindless chore that is unnecessarily complicated. The resulting gap in understanding is the reason why Corinne Manogue and Tevian Dray created the Vector Calculus Bridge Project [27], which serves to inform both camps about ways a consistent message can be taught. There is also a tendency in Physics to over-simplify, in order to create nice linear equations that are solvable, instead of including higher-order terms which make more physically-realistic equations that are difficult or perhaps impossible to solve numerically. While this lets us plug in numbers and make predictions, sometimes the results are misleading.

It is easy to see why fundamental asymmetry could be missed by Physics folks, in the context of the discussion above. The divide between the Math and Physics descriptions alone can account for a much of the misunderstanding that prevails, about applicable Maths, and the gaps in understanding that remain to this day. But the fact we missed the fundamental importance of asymmetry aptly explains why thermodynamic entropy is considered somewhat an oddball or outcast subject in mainstream Physics [28]. The good news is that we don't need to throw away any of what we learned studying linear phenomena to go beyond the limitations of our current understanding; we need only recognize that there is a range of natural phenomena for which a larger palette is needed.

Luckily, it is also seen that the pieces fit together, uniting the symmetry-based picture with the asymmetric one, because the Mandelbrot Set reproduces Cartan's rolling-ball analogy for G_2 symmetries, at (-0.75,0*i*) where the circular region rides on an arc with a radius three times as large. Since G_2 is the automorphism group of the octonions, one would like to find a connection, and indeed in 1995 Kricker and Joshi showed that $\mathcal{M}$ allows us to plot associative and non-associative regions for the octonion quadratic [29].

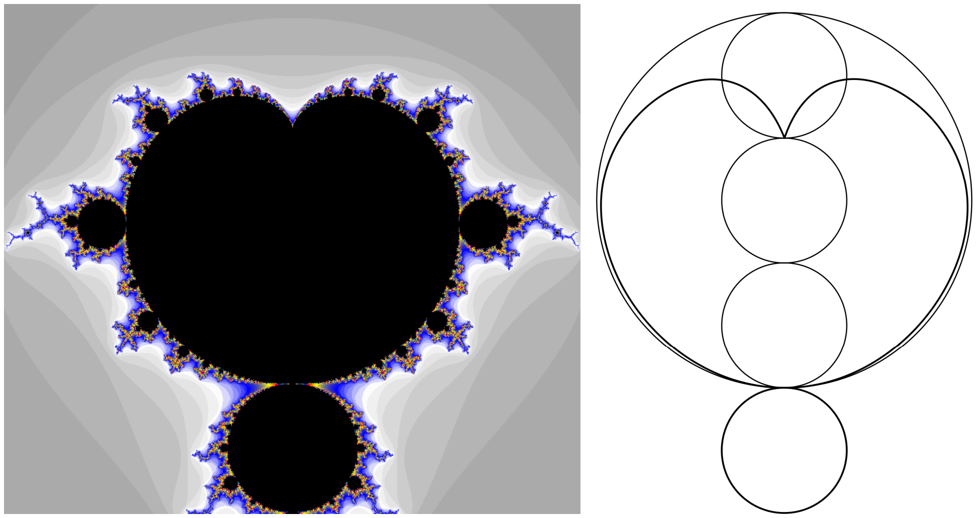

Fig. 1. The Mandelbrot Set illustrates Cartan's G_2 rolling-ball analogy

Perhaps the most compelling evidence for the maximal asymmetry of $\mathcal{M}$ is obtained by overlaying the Mandelbrot figure with the bifurcation diagram obtained using the same formula over the real numbers. What is seen is that there is a split or bifurcation at each point where the boundary of $\mathcal{M}$ folds back on itself, along the real axis, when tracing a path from the cusp to the tip at (-2,0*i*). This was eye-opening for me, when I first saw it in the pages of "The Beauty of Fractals" by Peitgen and Richter [30]. But just as striking is the place where the trajectories all appear to merge, at the Misiurewicz point $M_{3,1}$ near (-1.543689,0*i*), which is unassuming yet could be consequential. This is the location I now see as the condensation point of gravity, after reading the papers by Dvali and colleagues treating Schwarzschild event horizons as the quantum-critical point in Bose-Einstein Condensation.

The analogy of BEC formation and black hole event horizons is something I spotted in my studies of $\mathcal{M}$, long before I read Dvali's papers, or the earlier work by Sakharov. I was reluctant to explore that analogy in academic papers, however, until I had seen it demonstrated that this could lead to worthwhile Physics, but later it became a central point of my talk at FFP15. Furthermore; I see condensation as a general feature of all theories of emergent and induced gravitation, such as entropic gravity. If gravity arises this way; the thermodynamics leads naturally to a condition where condensation and gravitation are seen to coincide.

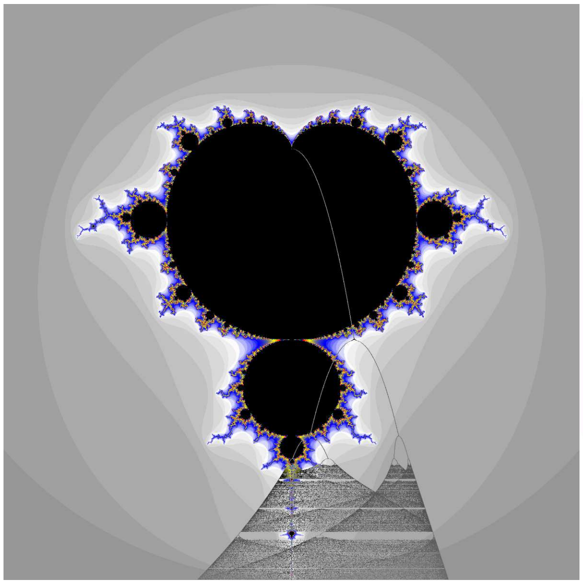

Fig.2. Mandelbrot Set with its bifurcation diagram

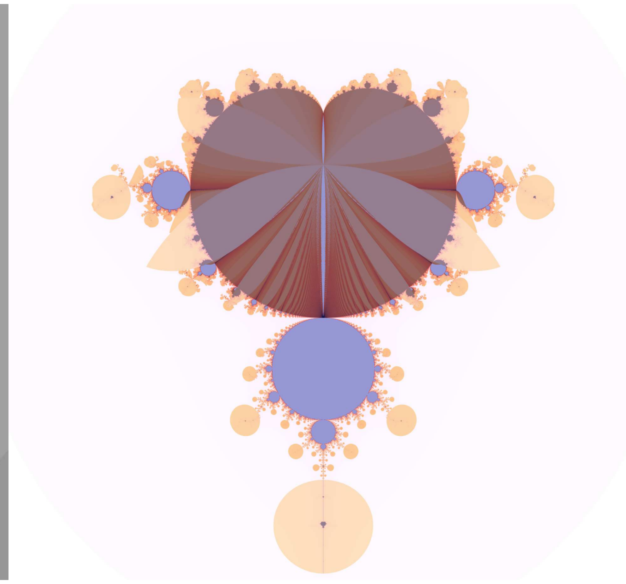

Fig. 3. Mandelbrot Butterfly highlights diminishing iterands

Weaving the Threads Together

If someone were to ask me whether I thought gravity was fundamental to our lives here as humans; I'd say 'yes' emphatically. In fact; I might go on about how upright walking evolved as a better way for humans to overcome the force of gravity, in order to deal with the world more flexibly. Whether gravity is essential for humans to continue living on the Earth does not affect its fundamental status in Physics though. Nor does it mean demoting gravity from being a fundamental force to a residual or consequence of other forces will stop people from looking for a theory of quantum gravity, or researching and searching for more complete unifying theories.

However; exploring the possibility that gravity can be explained as a consequence of other forces yields insights that help us to craft better unifying theories than we might otherwise – if that option was off the table. The relevance of those insights likely reflects the pervasive presence of asymmetry in the natural world. I think that our preoccupation with symmetry has blinded some Physics folks to the value of asymmetry in Physics, and it will take considerable effort to learn the other side of the story. There is still a need to expand what we know about symmetry, and its value won't go away, so there is no threat to those studies. But the need to examine a range of possibilities beyond what symmetry can teach us is increasingly evident. It is possibly true that asymmetry is *equally* important, and *should* be regarded as a fundamental property.

When considering the question of what is fundamental in Physics, we are faced with determining what concepts regarded as essential can be cast away instead, without losing the utility they provide. Just because we learned them first, or believe them to be more basic, does not mean that all we imagine to be fundamental in Physics is actually part of what nature treats as foundational concepts. Nor does it imply every idea we perceive as fundamental cannot be derived. If perceived fundamentals can be recreated from simpler or more general notions, it is likely those new assumptions are actually more fundamental. But nature is tricky or surprising sometimes, and does not adhere to simple descriptions in every instance.

In his lecture at FFP10; Nobel laureate Doug Osheroff advised us that making advances in Physics requires us to assume that we don't know everything, to be cautious that the current crop of theories could be wrong, and so to actively explore other possibilities by examining unexplored regions of the parameter space [31]. In the present; I think the polar opposite of the conventional view based on symmetry is a good place to look, because asymmetry is as much a fundamental to Physics as symmetry is.

Is it reasonable to base our Physics entirely on symmetry, when we imagine that the cosmos is asymmetrical in time? If we observe the universe is thermodynamically open-ended, and assume a conventional cosmology, we face a cold dark end to the cosmos. Even if we allow for a cyclic cosmology, this does not change that the universe is different at its inception and the far point or apex of any cycle. So it is not entirely unnatural to assert that gravity emerged as the universe cooled in a process of fractionation from the unified force, where the action of gravity is seen as a condensation of energy at the gravitational radius of any massive body.

I remind the reader that there is, according to Relativity, a small volume at r_G to which all the lines of force converge, deep inside any object of conventional matter, but for a black hole with no spin or charge, this quantity is called r_S, the Schwarzschild radius – as its event horizon is at the radius of gravitation. I am guessing this type of astrophysical object (without spin or charge) is quite rare, or perhaps non-existent, in the current era, but that they will come to dominate near the universe's end. The analogy of a Schwarzschild horizon with the quantum critical point of BEC formation, suggested by Dvali and Gomez, means that we can view a gravitational action as a process of Bose-Einstein condensation, however. This is a very useful analogy that is the logical endpoint of various entropic or emergent gravity theories, including the earlier work of Sakharov.

Our ability to determine what is fundamental in Physics depends on our knowledge of reality and the cosmos. We have come a long way, and we know far more than we did, but we are taking in new data so fast it will be easy to miss important details if we are not careful. Even if we *are* careful; we are certain to miss a lot, given the petabytes of data we are now accumulating from astrophysical sensors and particle physics experiments. In addition to merely storing such enormous amounts of data, there is the difficulty of processing it all, and over time with being able to run software designed for outdated operating systems, or for hardware that no longer exists.

We are faced with daunting challenges, in this area, we are only marginally prepared to deal with at this time – and the problem is likely to get worse before it improves significantly. But the wealth of data we have already accumulated makes it clear we need to look even farther or deeper for answers, because there is so much we have yet to learn. We may need to re-invent Physics to keep up with what we know, or are learning. So it is timely to have a discussion on gravity's place within the hierarchy of fundamental forces and concepts within Physics, seriously considering that gravity may be a consequence or residual action rather than a fundamental force in its own right. If we are prepared to give up our comfortable certainty; we may learn something.

If we also consider seriously that asymmetry is a key to understanding Physics, this perhaps changes the status of gravity again, because then the gravitational action is seen to be an effect of this primary cause. If we accord deep asymmetry fundamental status, and gravity arises from this attribute, then gravity is more fundamental than the other forces. The fundamental status of deep asymmetry is consistent with what is observed in M, and gravity is the clearest example seen in analogies of the Mandelbrot Set with Cosmology and Physics. Since the Misiurewicz point involved is one of the few places in M that is analytically tractable to find an exact or precise solution for, we are lucky.

We can obtain both an exact analytical solution and a numerical solution of whatever precision we require for its location. But because the Mandelbrot Set and Mandelbrot Butterfly figures are computationally derived, and given that the algorithm can be varied to remove individual layers of the butterfly wings and discs or highlight other details, we can extensively study the behavior of variations at the Misiurewicz point near (-1.543689,0*i*). It appears to be a good analogy for both Bose-Einstein condensation and Schwarzschild event horizons. An array of specific Misiurewicz points may well-represent different types of black holes, if we follow this analogy out. This raises the possibility that the existence of the Mandelbrot Set is somehow essential to Physics. If the universe arises from mathematical order [32], and M is the counterpoise of the symmetry groups, the great symmetry-breaker and the embodiment of universal asymmetry, the Mandelbrot Set is truly fundamental to Physics.

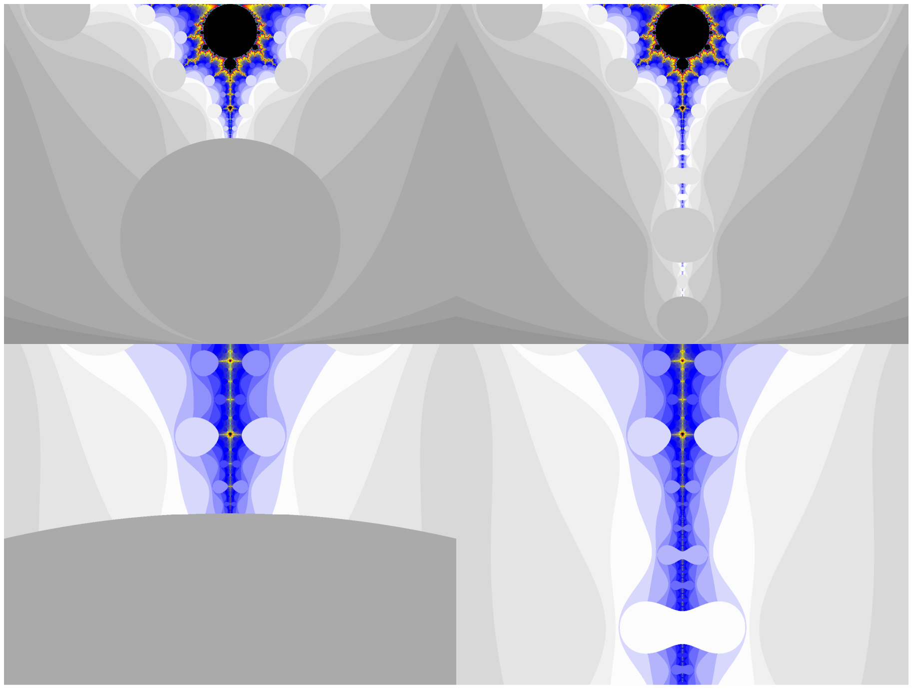

Fig. 4. Misiurewicz point illustrating Event Horizon (on left) and Condensation (on right)

I'm still unsure of whether gravity actually is a fundamental force of Physics or not, so I leave deciding that question up to you.

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Image Credits

Figure 1, 2, & 4 – images created by the author using Chaos Pro 4.0, Corel DRAW, and R
Figure 3 – semi-transparent Mandelbrot Butterfly image created by Paul Bourke

Additional Resources

Dvali, G., Gomez, C. – Black Hole's Quantum N-Portrait, arXiv:1112.3359, Dvali, G.; Franca, A.; Gomez, C.; Wintergerst, N. – Nambu-Goldstone Effective Theory of Information at Quantum Criticality, *Phys. Rev. D* **92**, 125002, 2015, arXiv:1507.02948; Dvali, G.; Panchenko, M. – Black Hole Type Quantum Computing in Critical Bose-Einstein Systems, arXiv:1507.08952; Dvali, G.; Gomez, C.; Lüst, D. – Classical Limit of Black Hole Quantum N-Portrait and BMS Symmetry, *Physics Letters B*, **753**, 10, February 2016, pp. 173–177, arXiv:1509.02114

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Dickau, Jonathan J. – 'Condensation,' a downloadable video segment showing animated Julia Set view of Butterfly figure, where two discs are seen to merge, with a brief pause at the Misiurewicz or quantum critical point; 'Tail Zoom Reveal,' a downloadable video segment showing the Mandelbrot Butterfly zooming in near our Misiurewicz point of interest, where layers of discs are stripped away then restored.

Footnotes

On pg. 2, regarding Noether's theorem linking conservation laws and symmetry –

* - For all systems describable by a Lagrangian or Hamiltonian, which includes the vast majority of what Physics studies. While sometimes applied more generally, this is often erroneous and should be avoided.

Notes on Entropic Gravity

One can show simply how entropy and gravity are related, with the 'spreading and sharing of energy' metaphor. A stone lifted above the Earth has all its potential energy concentrated in a small volume, where the PE varies with the square of the distance, or height, to which it is lifted. But once the stone is dropped and strikes the Earth; the same energy is spread over a larger volume and shared with a larger object. For a more technical treatment, we must introduce some background. One difference between Einstein's Relativity and Newtonian gravity that was stressed by Eddington is that gravitational lines of force do not converge to a point, in massive objects, but rather are seen to approach the rim of a small volume at the radius of gravitation r_G. As was mentioned; we call this feature the Schwarzschild radius for black holes, and denote it as r_S, which is given by the relation: $r_S = \frac{2MG}{c^2}$. But the horizon at this limit is seen to have some interesting properties. First; objects spread out entirely, flattening from 3-d to 2-d along the way. And second; the surface area is quantized at the Planck scale, and so is entropy, such that discrete changes in entropy are accompanied by Planck-area sized jumps in the black hole surface area.

It was also found by Hawking and Bekenstein that the thermodynamics of black holes was more interesting than first thought, where these objects have a temperature and emit black-body radiation. A black body is something that absorbs all light or other radiation when cold, but will glow brightly when heated to a high enough temperature. Later Unruh found, however, that this temperature is not an absolute but will vary depending on the observer's acceleration toward, or away from, such a massive black-body object. This relation allows us to find a correspondence between any gravitational acceleration and a temperature change that we can then use to forge a link between thermodynamic variables and equations of motion like Newton's laws. So using the above and following Verlinde, Newton's universal law of gravitation can be straightforwardly derived.

$N = \frac{A}{l_{Pl}^2}$ where $l_{Pl} = \sqrt{\frac{\hbar G}{c^3}}$ yields $N = \frac{Ac^3}{\hbar G}$ using $E = \frac{1}{2} NkT$ and

information bits at horizon — degrees of freedom — equipartition theorem

knowing $E = mc^2$ using $T = \frac{\hbar a}{2\pi ck}$ $A = 4\pi r^2$ $F = ma$ we obtain $F = G\frac{mM}{r^2}$

use equivalency — and Unruh for T — keeping in mind — Newton's law of gravitation

Notes on the Mandelbrot Set and Physics

While known to many Physics folks, the Mandelbrot Set is not usually thought of as relevant to Physics, as the Lie groups are. What is seen by those who delve into its mysteries, however, is often applicable to the study of physical processes. So it would be nice to see $\mathcal{M}$ regarded more broadly as relevant for insights into Physics. It should be remembered that the Mandelbrot Set we see is a shadow or projection of a higher-dimensional figure, the hyper-complex versions of $\mathcal{M}$ living in the Quaternions and Octonions. Furthermore, as shown by Kricker and Joshi; the Mandelbrot Set serves as a way to map quadratic algebras in the Octonions, to find where things commute and associate, and where non-commutative or non-associative behaviors come to dominate. So I plan to investigate this further.

I think of a lot of the Physics analogues that I have seen for $\mathcal{M}$ happen because of the way the 2-d version of the Mandelbrot Set tells us about the workings in higher dimensions. It informs us of their nature by enfolding via self-similar projection the higher onto its lower-dimensional representations. This is an expression of the fact that fractals are a way to encode higher-dimensional information and complexity onto lower-d forms, or to compress content in higher-d forms so that more of information can fit into their lower-d projections, in general. But the Mandelbrot Set for $z \to z^2 + z$ is somehow archetypal as the granddaddy of forms of its kind, being more complex and articulated than that for any other polynomial, or other common algebraic expression, under iteration. So we have a lot to learn, in terms of the interplay of preserved and broken symmetry, because $\mathcal{M}$ is full of examples where structures are highly symmetrical when magnified yet highly asymmetrical at lower magnification. This is useful knowledge for people doing Physics.

The document above is essentially unchanged from the essay that was a finalist in the FQXi 2017-2018 contest asking "What is Fundamental?" in Physics. Typographic or factual errors were corrected, and some awkward phrases were re-worded to improve readability, but the core arguments remain unchanged and additional findings or sources discovered in the interim were not included.