Qbe: Quark Matter on Rubik's Cube *

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Abstract

Quarks can be represented on the faces of the 3x3 Rubik's cube with the help of a symbolic representation of quarks and anti-quarks, that was delevoped originally for a deck of elementary particle cards, called Quark Matter Card Game. Cubing the cards leads to a model of the nearly perfect fluid of Quark Matter on Rubik's cube, or Qbe, which can be utilized to provide hands-on experience with the high entropy density, overall color neutrality and net baryon free, nearly perfect fluid nature of Quark Matter.

1 Introduction

In 2011, Cs. Török, a 17 years old secondary school student in studying Gyöngyös, Hungary invented a card game with elementary particles [1]. By 2014, this Quark Matter Card Game became an invention, a patent and a product. Initially, four different kind of games were described in the first edition of a the book "Quark Matter Card Games - Elementary Particles, Playfully" playable with the same deck of 66 cards, representing elementary particles from the Standard Model of particle physics. By now about a dozen of various card games are invented, all based on the same deck of Quark Matter Card Game. Some of these games are described in the public domain, like the memory style quark matter card game [2] (where

*Dedicated to the 10th anniversary of the discovery of the perfect fluid of quarks at RHIC as well as to the 40th anniversary of the invention of Rubik's Cube.

pairs or triplets of particle cards are to be remembered) and its advanced version, called "Find your own Higgs boson" [3] where a Higgs boson is identified from its leptonic decay modes, that requires to remember four cards in an advanced, memory style game. In the so called Quark Matter Card Game, Figure 1, the players can familiarize themselves not only with some of the elementary particles that are the fundamental constituents of matter, but also with the properties of Quark Matter, the recently discovered new phase of matter, that behaves not as a gas but as a perfect fluid of quarks. Such a perfectly flowing Quark Matter filled our Early Universe just a few microseconds after the Big Bang. In 2004, this old-new state of matter was discovered in high energy heavy ion collisions at the RHIC accelerator at BNL, located on Long Island near New York, NY, US. Subsequently, the properties of Quark Matter were confirmed at larger colliding energies at the LHC accelerator, located beneath the France-Switzerland border near Geneva, Switzerland.

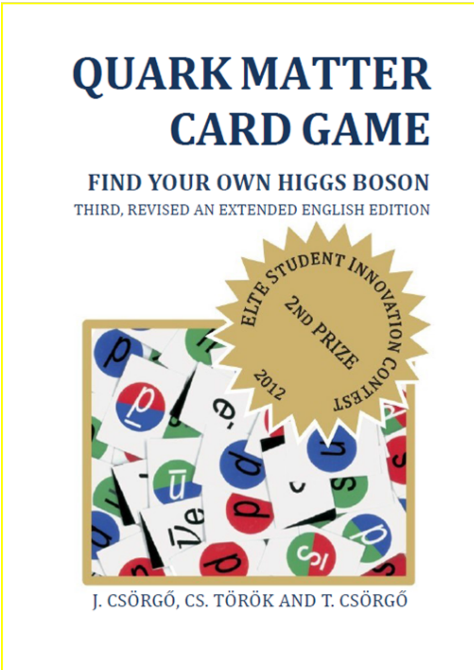


Figure 1: English language edition of Quark Matter Card Gamethat describes games with a deck of elementary particle cards, including a model the Early Universe just a few microseconds after the Big Bang [1]. Pick up a deck of Quark Matter Cards and you can play heavy ion collisions too, for a tiny fraction of the cost of doing an actual experiment at the RHIC or LHC accelerators.

Recently, an outdoor game called "Quark Wars" was also developed and tested, that utilizes the deck of Quark Matter Cards. Quark Wars is modelled on the so called "Hungarian number wars" outdoor game, with notable influence of the American epic space saga "Star wars" [4].

In addition to being a contribution to the proceedings of the WPCF 2014 conference, this manuscript is also an extended and updated version of a handout booklet, distributed by the Guests, Users and Visitors Center of Brookhaven National Laboratory at the 2015 AGS and RHIC Users Meeting, that was dedicated to the 10th anniversary of the publications of the so called RHIC White Papers, announcing the discovery of the prefect fluid of quarks [5, 6, 7, 8].

2 Anniversaries

In 2014, we celebrated several anniversaries:

- 1944, 70 years before: Ernő Rubik was born in Budapest, Hungary [9].
- 1954, 60 years before: CERN, the European Laboratory for Particle and Nuclear Physics was founded [10].
- 1974, 40 years before: Mr. Rubik created the prototype of his cube [9].
- 2004, 10 years before: The perfect fluid of quarks was discovered in gold-gold collisions at BNL's RHIC accelerator [5, 6, 7, 8]

In the followings we present, how one can "dress up" or decorate a 3x3 Rubik's Cube with colored quarks and anti-quarks, using a symbolic notation of quarks and anti-quarks, as developed for the Quark Matter Card Game. This manner, Rubik's Cube becomes Qbe, a model or a symbolic representation of Quark Matter on Rubik's 3x3 Cube, corresponding to a special Cube dedicated to the promotion or popularization of the properties of the Perfect Fluid of Quarks.

The Perfect Fluid of Quarks or Quark Matter is the hottest known form of matter ever made by humans, with temperatures reaching above 5×10^{12} Kelvin in heavy ion collisions at CERN LHC [11]. Such a prefect fluid of quarks has been detected in the debris of high energy heavy ion collisions at BNL's RHIC accelerator and the results were confirmed at larger initial colliding energies at CERN's Large Hadron Collider (LHC). The perfectness of Quark Matter corresponds to its flowing properties: the natural, internal scale of dissipative motion called kinematic viscosity of this fluid is found to have the lowest value from among the known, human-made materials.

This conference contribution was first presented in 2014, at the 10th Workshop on Particle Correlations and Femtoscopy. By now, quite some time has been passed since 2014, but at that time it was natural to dedicate the Quark Matter Cube (in short, Qbe) to the 10th anniversary of the Perfect Fluid of quarks created in gold-gold collisions at BNL's Relativistic Heavy Ion Collider. The artist's view of Qbe is presented on Figure 2 .

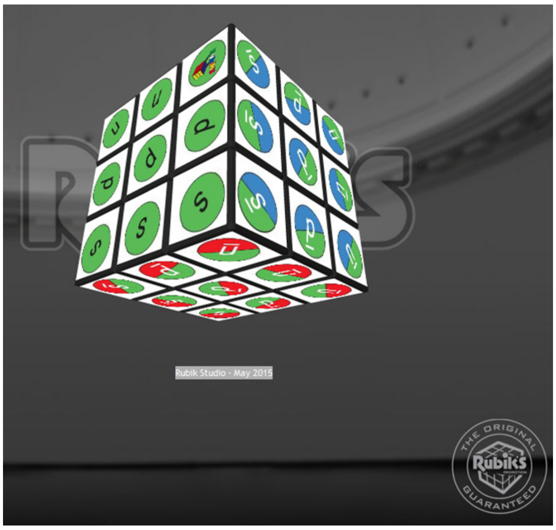


Figure 2: Qbe, the Quark Matter Cube, representing the perfect fluid of quarks that filled the our Universe just a few microsecond after the Big Bang. Image and the corresponding animation of Qbe is the courtesy of Rubik Studio Ltd., [12].

3 Quark Matter on Rubik's Cube - Playfully

Our current knowledge about the fundamental constituents of matter is summarized in the so-called Standard Model of Particle Physics. The elementary particles of the Standard Model can be arranged in the form of a 4x4 table, where the first 3 columns represent the three generations or families of matter-like particles (fermions) and the last column represents the interaction-mediating particles (bosons).

A playful representation of the most frequent matter-like particles was worked out in the year of 2011, in the form of so called Quark Matter Card Games, as illustrated on Figure 3. This representation is detailed in refs. [2, 3].

In 2012, as an extra bonus to this 4x4 table, the last missing piece, the so called Higgs boson of the Standard Model was also discovered experimentally. A card game that popularizes the discovery of the Higgs boson is detailed elsewhere [3]. Here we focus on the gamification and modelling of the properties of Quark Matter, the perfect fluid of quarks discovered at RHIC and confirmed at LHC.

The theory of the strong interactions, Quantum Chromo Dynamics (QCD) has some mathematical properties that are analogous to the properties of the optical colors. Due to this mathematical analogy the quarks can be modelled with cards that have optical colors: quark cards are colored to red, green and blue, the three fundamental colors in the RGB color space. One of the exact laws of QCD is that only those combinations of quarks are experimentally observable, that correspond to a color neutral (white) combination of quarks. One should also emphasize that Color in Quantum Chromo Dynamics is not to be confused with the visible, optical colors, but it can be understood as an optical model or analogy that reflects well the mathematical properties of the physical theory QCD and that analogy is used here to model strongly interacting fundamental particles called quarks and anti-quarks.

For an introduction on the birth of the quark concept that lead the way to the development of QCD as the theory of strong interactions as well as to the first ideas

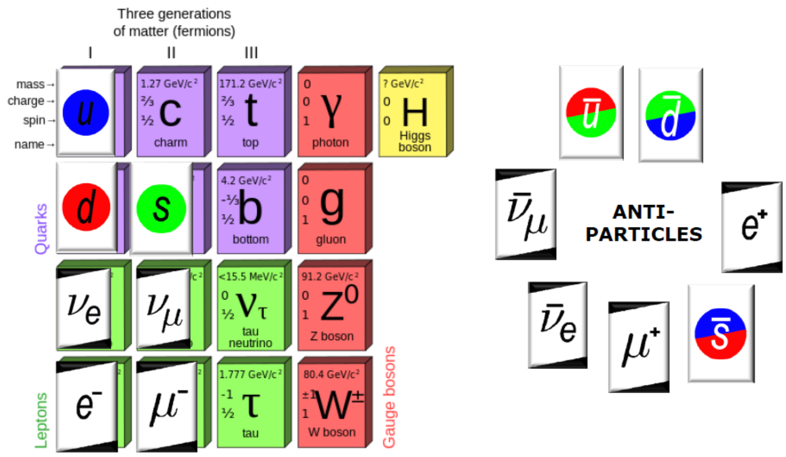


Figure 3: Elementary particles of the Standard Model – playfully, using the representations in the Quark Matter Card Game. Anti-particle representations are also included.

on the analogy of optical colors to model certain symmetry properties of the strong interactions, we recommend two early articles by Zweig and Gell-Mann [13, 14].

Importantly, another exactly satisfied law of elementary particle physics states that for each particle, a there exists a corresponding anti-particle, which is opposite in each properties to the given particle. For example, electron is an elementary particle with negative charge, so its antiparticle, the positron has a positive charge. But what is the opposite color to the red color? In the Quark Matter Card Games, we have chosen a combination of green and blue colors to model (symbolically represent) the anti-red color, because the green and blue combination supplements red to form a neutral, white color. Similarly, anti-green is defined as a combination of blue and red, while anti-blue is a red-green combination. Three major groups of color neutral or white particles can be formed: mesons or quark-antiquark color white bound states, baryons (bound states of red, green and blue quarks) and anti-baryons (bound states of anti-red, anti-green and anti-blue quarks), as indicated on Figure 4.

With the help of the colored quarks and antiquarks, and the six faces of Rubik's cube, one create a customized version of Rubik's cube in the following manner: Three faces that join in a single corner of the cube are selected to have red, green and blue colors. The diagonally opposite corner of the cube is selected to be the place where the anti-colored faces meet. The three most abundantly produced quarks (u, d and s) are also indicated on these little faces. The coloring scheme for the cube is such that quarks with a given color are on opposite faces with anti-quarks with the corresponding anti-color. For example the red quarks are opposite to the green/blue anti-quarks. Thus the opposite faces of Qbe combine to a white color, hence Qbe has an overall white color. This design, or the dressing up of Rubik's cube as Qbe or Quark Matter Cube is laid out on Figure 5.

Such a design can be well compared to the color scheme of the original Rubik's cube. This is illustrated on Figure 6. The Rubik design is dressing up opposite faces with color and color + yellow color: the white face of Rubik's cube is opposite to

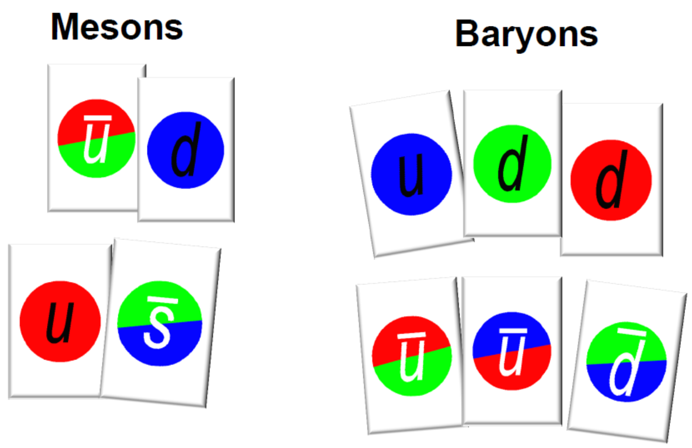


Figure 4: Mesons are colorless (white) combinations of a quark and an antiquark, that is represented in the Quark Matter cards as a red, green or blue quark card matched with an anti-red (green/blue), anti-green (blue/red) or anti-blue (red/green) pair of cards. Baryons are represented by a red, a green and a blue quark card, forming also a colorless (white) combination of three quarks. Anti-baryons are also colorless, they can be formed from an anti-red, anti-green and anti-blue Quark Matter card.

the yellow, red is opposite to orange and the blue face is opposite to the green face. On Qbe, the three faces with the fundamental red, green and blue colored quarks are placed opposite to the three faces with the fundamental anti-colors: anti-red, anti-green and anti-blue. This color scheme of Qbe reflects faithfully the overall color neutrality or whiteness of Quark Matter.

In the Early Universe, just a few microseconds after the Big Bang, Quark Matter is created in a special way, namely the number of quarks and the number of anti-quarks were almost exactly the same at that time. This is property of the Early Universe is faithfully represented: on Qbe the number of quarks is exactly the same as the number of antiquarks, as apparent from Figure 5. In the deck of cards of the Quark Matter Card Game, the number of quarks is larger than the number of anti-quarks, corresponding to the properties of Quark Matter created in high energy heavy ion collisions at man-made accelerators.

The mathematical properties, namely the possible number of color configurations on Rubik's cube are compared to the properties of Qbe on Figure 7. We emphasize that the position of the u, d and s quarks in a heavy ion collision is physically a relevant quantity as the masses and other properties of these quarks vary. So we suggest to distinguish the physical orientations of Qbe, which gives an extra 6x4 = 24 factor for its number of states. In addition, due to the u, d and s letters written on the facelets to represent quarks, the face-center facelets are oriented so the total number of possible configurations of Qbe, the Quark Matter cube is larger than the number of states on Rubik's cube. The logarithm of the number of states corresponds to the entropy content of these cubes. The entropy divided by volume defines their entropy density.

The entropy density of Qbe the perfect fluid of quarks on Rubik's 3x3 cube can

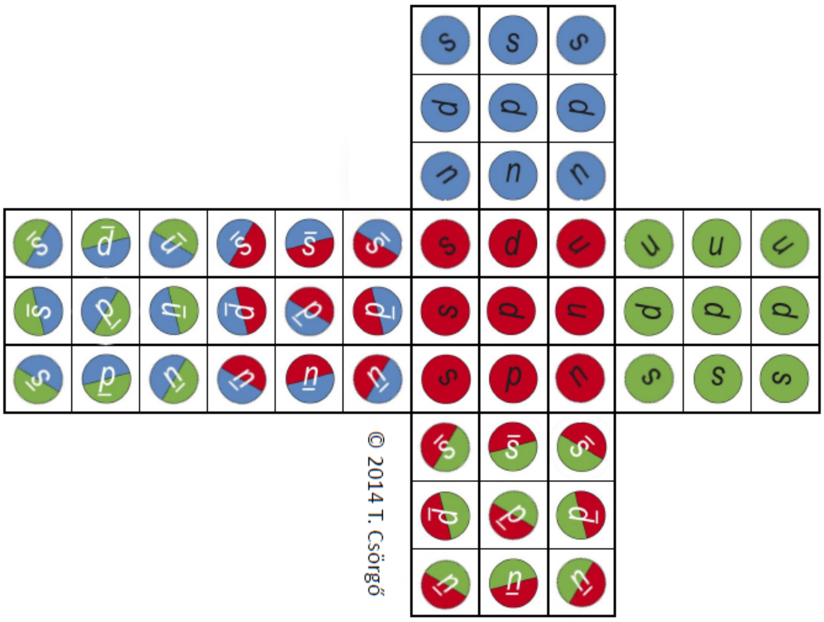


Figure 5: Layout of Qbe, the perfect Fluid of Quarks on Rubik's 3x3 Cube.

be compared to the entropy density of quark matter created in heavy ion collisions at RHIC and LHC accelerators. To have the same entropy density as Quark Matter, Qbe should be scaled down too much, from 57 mm to 2x10^{-12} m, but instead of scaling the cube down, we suggest use Qbe as a model of Quark Matter that fits

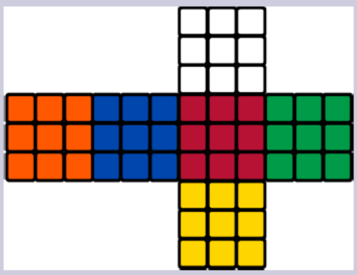
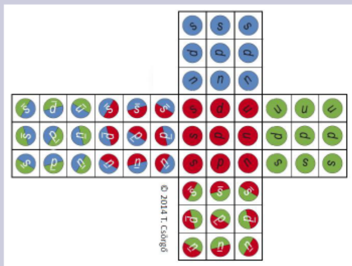
Original Rubik's Cube	PF Quarks Cube
	
(red, orange)	(red, anti-red)
(white, yellow)	(green, anti-green)
(blue, green)	(blue, anti-blue)

Figure 6: Comparison of the color scheme of Qbe with the color scheme of the original Rubik's 3x3 cube.

suitably the size of our hands. The physical properties of Qbe the Quark Matter Cube can thus be compared also to the physical properties of Quark Matter, as summarized on Figure 8.

Original Rubik's (magic) cube: 3x3x3 cube, 6 colors 8 corner cubes: 3 colors, 3 positions 12 edge cubes: 2 colors, 2 positions 6 face centers: 1 color, 1 position Even permutations only!	**Quark matter (fluid) cube:** 3x3x3, 3 colors+3 anti-colors 8 corner cubes: 3 colors, 3 positions 12 edge cubes: 2 colors, 2 positions 6 face centers: 1 color, 4 positions Even permutations only!
Corner cubes: 8! permutations $3^8/3 = 3^7$ possible orientations Edge cubes: 12! permutations $2^{12}/2 = 2^{11}$ possible orientations Face centers: no orientation Cube: indifferent global orientations	Corner cubes: 8! permutations $3^8/3 = 3^7$ possible orientations Edge cubes: 12! permutations $2^{12}/2 = 2^{11}$ possible orientations Face centers: $4^6/2 = 2^{11}$ orientations Cube: 6x4 different orientations
Number of possible states: $8! \times 3^7 \times 12! \times 2^{11} \times 1 \times 1 / 2$ $\sim 4.3 \times 10^{19}$	Number of possible states: $8! \times 3^7 \times 12! \times 2^{11} \times 2^{11} \times 24 /2 \sim$ 2.1×10^{24}

Figure 7: Comparison of mathematical properties of Qbe and Rubik's Cube.

	Original Rubik's Cube	**PF Quarks Cube**
Number of states, N	43252003274489856000	2125922464947725402112000
Entropy, S = ln N	~ 45.21	~ 56.02
Length, L [mm]	57	57
Entropy density $\sigma = S/L^3$, [m^{-3}]	$\sim 2.4 \times 10^5$	$\sim 3.0 \times 10^5$

Comparison to Nature	**Perfect Fluid of Quarks**
Energy density, ε [GeV/fm^3]	15
Speed of sound, c_s^2	0.1
Temperature, T [GeV]	0.22
Entropy density $\sigma = (1+c_s^2)\,\varepsilon/T$, [$m^{-3}$]	7.5×10^{46}

For a perfect model:
$L' = L/ 25^{1/3}/10^{10}$
$L' \sim 2\times10^{-12}$ m

Figure 8: Comparison of physical properties of Qbe and Rubik's Cube.

4 Discussion

The connection between the symmetry properties of quarks and Rubik's cube with twisted corner pieces has been noted by Golomb already in 1981 [15]. His article determined the number of color configurations on Rubik's cube as well. Marx and collaborators considered Rubik's cube as a kind of world model, with conservation laws and transformation rules and they noted how baryons and mesons might be represented with Rubik's cubes with twisted corner or edge cubelets [16]. Hofstadter picked up the idea of Golomb and noted the importance of variations on the same theme as a key element to innovation. His 1982 article made Rubik's Cube with a twisted or "quarked" corner piece to the cover page of Scientific American [17]. However, as far as we know, Quark Matter with colored quarks and anti-quarks was not considered in the context of a Rubik's cube before.

Although the mathematical and engineering aspects of the Rubik's cube were summarized already in 1987 by E. Rubik and collaborators [18], some of the mathematical aspects of the Rubik's cube imposed deep and difficult problems. For example, the minimum number of rotations that are needed to reach any given configuration from a perfectly ordered Rubik's cube (the so called God's number) was proven to be 20 by Rokicki only in 2014 [19]. As far as I know the God's number for Qbe or other generalized Rubik's cubes with oriented face centers is not yet determined.

The educational values of Rubik's cube in visual-spatial intelligence, developing strategy, improving memorization, concentration and persistence in problem solving as well as the marketing values of Rubik's cube in popular Science, Technology, Engineering and Mathematics (STEM) were overviewed recently in ref. [20].

Let us mention, that Rubik's cube was recently envisioned as a model for describing the change of the interiors of black holes while emitting a Hawking particle and thus decreasing the size and corresponding the entropy of a black hole. This processs was conjectured to be analogous with solving the Rubik's cube [21]. This analogy between an evaporating black hole to vacuum and solving the Rubik's cube from a large initial entropy / disorder to a color ordered, zero entropy state may provide further inspiration for follow-up STEM gamification and outreach studies.

To illustrate that quite some time and wisdom might be needed to solve Qbe, let us estimate how many rotations might be needed in every second, if we would try to solve it just by random rotations. Our Universe is about 13.8×10^9 years old and the number of states on Qbe is given in Figure 7 as approximately 2.1×10^{24}. As the lifetime of our Universe converts to about 4.35×10^{17} seconds, one would need to rotate the Qbe a littlebit more than 4.8 million times in every second, for the entire lifetime of our Universe, to be able to solve it just by random rotations. Such a tremendous mindless effort can be contrasted to the various records of solving Rubik's cube using skillful means in speed cubing championships: The current world record for single time on a $3\times3\times3$ Rubik's Cube was set by Feliks Zemdegs of Australia in December 2016 with a time of 4.73 seconds at the POPS Open 2016 competition in Melbourne, Australia [22].

Let us close this article by noting that what we discussed here was just a toy or a toy model, that does not have to be taken too seriously. In this sense this outreach article is quite similar to many studies in science. A model is just a model, reflecting certain properties of the reality and is best understood with a certain smiling playfulness, similar to the mysterious smile on the face of Mona Lisa. The Road to Reality is often a difficult one but our journey may become much more enjoyable, perspiacious and lightsome if we proceed with a touch of smiling wisdom, as illustrated on Figure 9.

The Appendix of this contribution is organized as a handout booklet, to be distributed with Qbes or Quark Matter Cubes.

Acknowledgments

Inspiring discussions with S. Kiss are greatfully acknowledged. The presentation of Quark Matter on Rubik's 3x3 Cube at the WPCF 2014 conference in Gyöngyös, Hungary has been partially supported by the OTKA NK 101438 grant.

Availability

Limited number of Qbes, Quark Matter on Rubik's Cubes were distributed first as promotional gifts to the participants of the WPCF 2014 conference in Gyöngyös, Hungary. As science outreach gifts, they are also made available at the BERA Shop in the Berkner Hall at Brookhaven National Laboratory, Upton, NY, USA, since June 2015. A limited number Qbes is available just as well in the Iijima Shoten in KEK, Tsukuba, Japan.

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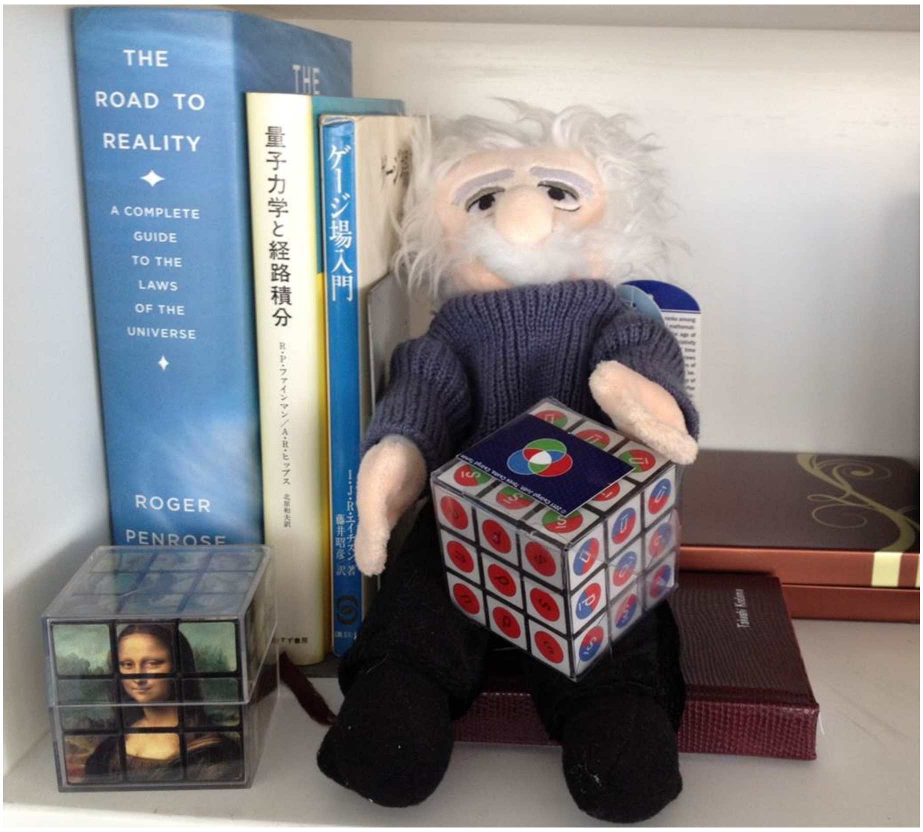

Figure 9: Figure of Albert Einstein, the smile of Mona Lisa and Qbe: Quark Matter on Rubik's 3x3 Cube, next to the Road to Reality: A Complete Guide to the Laws of the Universe. Photo courtesy of prof. T. Kodama, Rio de Janeiro, Brazil.

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Handout for Qbe: Quark Matter on Rubik's Cube

Perfect Fluid Promotion: Qbe or Quark Matter on Rubik's 3x3 Cube is not only fun but also a promotional tool to introduce and illustrate certain unusual properties of the perfect fluid of quarks. A perfect fluid can flow without internal dissipation. So the perfect fluid of Quark Matter could be modelled faithfully by a perfectly lubricated Rubik's cube, suited perfectly for speed-solving competitions.

Number of players: Typically one person, but speed and memory cubing competitions can be organized.

Object of the game: The goal is to solve a fully scrambled Qbe - Quark Matter on Rubik's 3x3 Cube by reaching its color-flavor-locked ground state. Flavor locking means in this context that the letters representing d flavoured quarks on the face-center facelets should point towards the corner of where the red, green and blue faces meet and the letters $\overline{d}$ that stand for anti-d antiquarks on the face-center facelets of the anti-colored faces should simultaneously be pointing to the opposite corner of Qbe, where faces with anti-red, anti-green and anti-blue colors meet.

The course of the game: The players inspect the thoroughly scrambled Qbe, then place it back to the desk in front of them. They may use any of the agreed methods (both hands, or in extreme cases, single hand, both feet, blindfolded, underwater and so on) to solve Qbe. By rotating the sides of Qbe, they compete to reach the desired (color ordered or color-flavor locked) ground state of Qbe.

Qbe, the Quark Matter on Rubik's 3x3 Cube is a three dimensional combination puzzle that can be solved on beginner, intermediate or advanced levels:

1) *On beginner level,* players do not know the how to solve the standard Rubik's Cube. It is a challenging task to figure it out on your own, but it is worth to try. Physicists or physics students are expected to be able to do the first layer on their own and some may even be able to do the second one without too much effort. Doing all the three layers on his own lasted several weeks even for Mr. Rubik himself, but these days there are several public videos that show how to solve the cube, see for example `https://www.youtube.com/watch?v=rmnSpUgOvyI`. This way the players will be able to solve the colors of Qbe. However, the orientation of the d-quarks on the center facelets on each face may still point to random directions.

2) *On intermediate level,* the goal is to reach the color-flavor locked ground state. In this case, after the faces are color ordered, all the d quarks in the centers should point to the corner where the red, green and blue colors meet, and all the anti-d quarks should point to the opposite corners, where the faces with anti-red, the anti-green and anti-blue colors meet. This means that the players have to change the orientation of the center pieces on the faces of the cube without destroying the color order. This is also an already solved problem, sometimes referred to as solving the Super-Cube, custom-cube or picture-cube. Without significant cubing experience, physicists are not expected to figure this out on their own. To fix the direction of the centers, see e.g. `https://www.youtube.com/watch?v=fk1eCZNCTB4` .

3) *On an advanced level,* the players already know how to solve Qbe. But they can still improve the time they need to do so, they can try to do this blindfolded, by one hand, or may use any other of the several mind-boggling methods that were developed recently for the emerging arts of speed and memory cubing.

Recommended physics talking points are listed as follows:

1. **Color:** Quark Matter is a colorless state, but locally colors are free, deconfined, as most of the cubelets have a net color. Qbe is decorated by colored

quarks and anti-colored anti-quarks to illustrate a state of matter called Quark Matter or Perfect Fluid of Quarks. Quarks come in three different colors: red, green and blue. Antiquarks have anti-colors called anti-red, anti-green and anti-blue, represented by the combination of green/blue, blue/red and red/green colors, following the model developed for the Quark Matter Card Games [1, 2, 3, 3]. In the ground state, the red face of Qbe is opposite to the anti-red, blue face is opposite to anti-blue, green is opposite to anti-green. In a random state of Qbe, locally the colors are not compensating each other to a color neutral, white or red-green-blue combination, however, adding all the colors on Qbe results in an overall, globally white color, that models faithfully the globally color white but locally colored property of the Quark Matter state.

2. **Flavor:** Quarks may have 6 different flavors, denoted as u, d, s, c, t and b. On Qbe, only the first three flavors are utilized: u, d and s. These flavors correspond to the flavors of the most abundantly produced quarks at RHIC and LHC. Can you order the faces of Qbe by the flavor?

3. **Baryon number:** The net baryon number of any system of quarks is defined as the number of quarks minus the number of anti-quarks, divided by 3. What is the net baryon number of Qbe in its ground (ordered) state? Do rotations (that mix the quarks and antiquarks of Qbe) modify its net baryon number?

4. **Entropy density:** Quark Matter has a huge entropy density, $\sigma \approx 7.5 \times 10^{45}/\mathrm{m}^3$. This can be compared to the huge number of physically different states of Qbe. When the 24 possible orientation of a given cube in space as well as all the possible orientation of the center pieces are also taken into account, the possible number of states of Qbe becomes a huge number: 2,125,922,464,947,725,402,112,000 ($\approx 2.12 \times 10^{24}$), a bit larger than Avogadro's number, 6.02×10^{23}. Derive the entropy density of Qbe, given that an edge of Qbe is 57 mm.

5. **Perfect Fluidity:** A fluid is perfect if it has no internal dissipation. The resistence of a fluid to internal friction/shearing motion is characterized by the so called kinematic viscosity, denoted by η/σ. This is somewhat analogous to the resistance of the faces of Rubik's cube to rotation: in a perfect model of a perfect fluid, a rotating outer third of the cube could keep on rotating forever, without resistance. Due to dissipative forces, this rotation is coming to an end shortly on a physical model like a Qbe. Use this analogy to estimate the kinematic viscosity η/σ of Qbe, the Quark Matter on Rubik's 3x3 Cube, if the torque needed to rotate an outer third layer of Qbe is of the order of 0.1 Nm and σ is the entropy density of Qbe evaluated in item 4 above. How far Qbe is from the conjectured quantum limit for a perfect fluid, $\eta/\sigma = \hbar/(4\pi)$?