The Blobfish Scenario

A very specific catastrophe in 7 chapters

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Dedicated to James Hoffmann and the 2005 *Nobel laureates in Physics.*

Homo mensura est.

Protagoras

Imagine a very specific catastrophe, in which every reference to our set of basic units has been suddenly wiped off the face of the earth. All the humans are gone too. Imagine further that the only survivors of this catastrophe are a group of not only sentient but unusually dexterous and highly motivated blobfish, with a strong interest in quantum mechanics and an equally strong preference for good coffee. The blobfish decide to begin measuring microscopic systems with maximal accuracy. Before starting their experiment, the blobfish, naturally, brew some coffee, but soon discover that they are caught in a bit of a chicken-and-egg conundrum.

They know that the best coffee is obtained after a brewing time of exactly 7 minutes, which they observe with a wrist watch one of the blobfish happens to own. Before measuring, they try to ensure that the watch is sufficiently accurate, even after the recent disruptions, by comparing it to another wrist watch, which was more expensive and is therefore, presumably, more accurate. Its owner happens to have lived in Lake Geneva for some time. The readings of the two watches diverge widely. Clearly, if started and stopped at the same time, they do not show that the same amount of time passed. But which of the two is right? The blobfish tend to accept the more expensive watch's result, but want to ensure its accuracy by comparing it to another, (even) more expensive clock. Also, when pushed, the other blobfish cannot quite remember *how* much more expensive this watch was, and whether he really bought it while staying in Lake Geneva at all.

The typical way out of such trouble would be to align the watch with a time-keeping device that is accepted as more trustworthy. This is the process of *calibrating* a watch. But how, in turn, is this more precise clock calibrated? The answer is: another, even more accurate clock. But how is *this* clock calibrated?…The blob-

fish get the idea. So, either every clock in the universe is just caught in an endless, self-referential cobweb, in which a common time can only be achieved by perpetually updating every single watch to match all the others, or there is a clock whose calibration *cannot* be doubted. A clock of *exact* time. In a time past, these were held by what was known as metrological institutes.

While the catastrophe has left all other infrastructure untouched, it has very specifically destroyed every metrological institute in the world. Admittedly, not much of a catastrophe to most people if they had still been around. To the blobfish, however, this poses a bit of an insurmountable challenge: Even if they *calibrate* their watch to display the same time as the more expensive watch, this watch would need to be calibrated itself. But to what? Not to the other watch, given it shows exactly the same time as the more expensive watch. The blobfish need an escape here. Until the blobfish have *defined* an absolute reference — the watch above which there are no more exact watches (if perhaps some more expensive ones) — no accurate coffee brewing will be possible. The quantum mechanics will have to wait too.

Time

The blobfish's original plan was to begin their project with the unit of voltage, volt [V], because they had observed that nearly all human measuring devices ultimately measured variables by recording a change in voltage and then used formulae to extract the information of interest. To their dismay, they soon realise that the volt is really comprised of several units, namely of current (ampere, A), mass (kilogram, kg), distance (metre, m) and time (second, s). They look up each unit's respective definition and discover a common theme: the ampere refers back to the kilogram; the kilogram back to the metre; and the metre back to the second. All of the units are themselves based on the precise definition of the unit of time. They thus decide to instead begin their project there. It will also be useful for brewing coffee.

They look up the definition of the second in their omniscient guidebook to the unit system the humans have left them with. They are surprised by what they find:

> The second […] is defined by taking the fixed numerical value of the caesium frequency, ν_{Cs}, the unperturbed ground-state hyperfine transi-

> tion frequency of the ^{133}caesium atom, to be 9192631770 when expressed in the unit Hz, which is equal to s^{-1}.

Not only is the definition of the unit quite complicated, given how immediately useful it proved to the blobfish, but it also refers to quite absurd numbers: 133 and 9192631770. The guide further explains that the number 133 is in reference to the atom with 55 protons, a.k.a. caesium (Cs), with $133 - 55 = 78$ additional neutrons as part of its nucleus. So far the blobfish are relieved: you do not need metrological institutes to count.

The other number, 9192631770, is stranger still and the blobfish wonder why humans did not use a more intuitive, one might even say a more *beautiful*, number, for such an important definition, such as 1 or 7. The guide is aware of the seeming absurdity of its definition and apologetically explains that this definition was adopted quite recently and had to be as similar to the already used convention as possible. The blobfish nod in approval and realise that the humans have made their definition of time conform to humans rather than making humans conform to their definition of time, which they find rather charming. They decide to make the blobfish unit system also as congruent as possible to the human system, not least so they can use all the humans' left-over equipment easily (except those in a competing human unit system, called «imperial», now an artefact of a bygone empire as well as a bygone species), and will therefore use the same strange number.

They lose some more time trying to figure out why the humans derived larger units of time based on groups of 60. In theory, the blobfish accept the utility of dividing all numbers into groups of 10, even though the argument for using 10 — that it makes counting things by hand easier — does not strike *them* as particularly convincing. They flip through the guide in search of an answer, but the humans apparently didn't consider this worthwhile to mention. The blobfish begin to suspect that the humans might have forgotten why themselves long ago.

They begin setting up the necessary experiment to measure time absolutely. Not without a certain anxiety, though, given the trauma the last calibration odyssey had caused them. The blobfish wonder: If this is supposed to be the most exact measurement of time possible *by definition*, would this not require the most exact calibration, too? Despite this, they struggle on and isolate a ^{133}Cs-atom connected

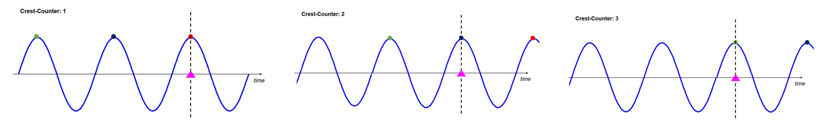

Abbildung 9.1: This figure shows what the blobfish see while performing their experiment. They choose an arbitrary point along the time axis that the device displays (here the pink triangle). They count every crest that passes through this point. At the first time point the red crest passes, then the blue, and finally the green. This corresponds to $\frac{3}{9192631770}$ of a blobfish-second.

to a device that can generate arbitrary frequencies, even if the blobfish cannot yet know the exact frequency expressed in any sort of unit.

To generate «frequency» actually means to generate waves with the particular property of having this frequency. We will see shortly what this actually means. For now, the blobfish trust that the savvy human engineers came up with a device that can generate any wave with any frequency. The blobfish now begin with a frequency of 0 and slowly make their way up to ever higher frequencies. This takes a long time (actually, an infinite time) because the blobfish use infinitesimal increments between frequencies. They decide to use discrete steps instead. The reason why they do this in the first place is because they know something *very* useful from the guidebook: the ^{133}Cs-atom absorbs a very specific frequency, which the humans refer to as the «unperturbed ground-state hyperfine transition frequency». This means that at some specific frequency, the atom will take in the wave and not let out any wave. The blobfish, therefore, observe the wave before and after it meets the atom, to see if it vanishes. The blobfish get lucky, and with their discrete intervals, they exactly hit the frequency, which has the human name $\Delta\nu_{Cs}$, and they see no wave after it meets the atom.

The blobfish rejoice at their success and are surprised at the ease of this experiment. One blobfish suggests celebrating the occasion by brewing some coffee. They realize, however, that they still haven't built a functioning clock. Fortunately, the device that allowed the blobfish to generate the frequency in the first place, can also display it as a series of crests and troughs, i.e., a wave. The meaning of this strange, but powerful number, 9192631770, now strikes the blobfish like a hairdryer underwater. They choose any arbitrary point on the horizontal axis and wait until 9192631770 crests (or troughs, for that matter) have passed through this point. The time they wait is *exactly* one blobfish-second or 1 bs.

This is where the blobfish's calibration odyssey ends. There is no imprecision in counting: one blobfish counting is not more or less accurate than another. (One can, of course, count the wrong stuff). A number of whole apples are either 3 or 4; for the number to be in between you would have to slice the apple up. *You can count without calibration!* This is where the bootstrap happens, and the entire unit systems pull itself out of the mud by its own hair, like the famous Götz of Berlichingen. A metaphor the blobfish find somewhat estranging.

They also realize that their device not only works as an exact clock but also quantifies frequencies. Any frequency can now be given a number based on how many crests pass through an arbitrary point on the horizontal axis *in one blobfish-second*. A frequency could now be referred to as «30 crests per blobfish-second», for example, or «30 bs^{-1}». If you want to call it by its human name, «30 Hertz». The blobfish now are truly relieved and finally set out to brew their coffee in *exactly* 7 minutes and ponder the significance of why the most fundamental unit of the humans measured the phenomenon they understood the least.

Length

The blobfish realize the importance of their work and set out to define other units too. They opt to next define the unit of length, the blobfish-metre or bm. They are pleasantly surprised by the ease of the definition given in their instructions:

> The metre is the length of the path travelled by light in vacuum during a time interval of $\frac{1}{299792458}$ of a second.

They also realize that its simplicity is only possible due to the heavy work they have already done in defining the second. Neatly, the definition directly describes the experimental set-up needed to define the metre: a vacuum space (of sufficient length) for a light beam to travel through for the duration of 1 bs. Such a device is quickly assembled, and the blobfish are only slightly annoyed by having to use another strange number, $\frac{1}{299792458}$.

But the blobfish accept that a more «beautiful» number would have meant a distance so long as not to be very useful, to either a human or a blobfish. They accept these numbers as quirks of any unit defined regarding universal constants, which rarely happen to fall into the narrow scope of human — or blobfish — experience. The necessity, however, of using these constants in the definition of the unit system, is now painfully clear to them.

They set up their vacuum space, and suck out all the air[i] and let a light beam start at the beginning of the chamber. One blobfish continually observes the light beam, ready to mark the distance it travelled by a line in the ocean sand, once another blobfish has counted the appropriate number of crests on the blobfish clock. The exact number of crests comes from the two strange numbers, so the blobfish will have to count $\frac{1}{299792458}$ of a fraction of 9192631770 crests. Which, to their sheer disbelief, turns out to be a very easily handled number, just above 30. Because the blobfish do not want to count partial fractions, they multiply the entire experiment by some number until they only have to count to a whole integer number. They simply divide the length travelled by light by this same number in the end, and thus they have defined the *exact* blobfish-metre. Bring on the quantum mechanics!

Mass

The blobfish seem to be on a roll and soon recognize a pattern: every subsequent unit they study is based both on some of the previous definitions, as well as some universal constant, be that a specific absorption frequency of a ^{133}Cs-atom or the speed of light in vacuum. They soon realize that this is also true for the unit of mass, the blobfish-kilogram or 1 bkg, which, though the humans ended up using their decadic system, actually is named as though it were been 1000 times the unit of mass. Which it is not, confusingly. As an additional downer, the blobfish soon realise that constructing an *exact* blobfish scale is slightly more complicated than the previous experiments, involving some old-school physics. Which fortunately does not pose too much of a challenge to our marine QM aficionados.

The universal constant they are after is the universal Planck constant h. Ironically, this constant gives the blobfish a very

[i] Which, unbeknownst to the blobfish, would break some fundamental laws of the universe. For ease of argument, we will let them have their unphysical victory in the knowledge that they could have repeated their experiment multiple times with different conditions and extrapolated the same finding from their data. It will not be the last time the blobfish will have to prevail over reality.

easy unit of energy, given that the energy of a frequency is simply its unit in bs^{-1} multiplied by h. But they get ahead of themselves. The blobfish are forced to do some quick algebra. As mentioned, they know how energy E relates to a frequency ν

$$E = h \cdot \nu. \tag{9.1}$$

They also know that any object of arbitrary mass m moving at a (in our case, constant) velocity v behaves as a wave, which in honour of a human — things are seldom named after blobfish — is called a de-Broglie wave. Thankfully, the frequency of this wave is also known

$$\nu = \frac{m \cdot v \cdot c}{h} \tag{9.2}$$

The blobfish get slightly nostalgic, once they realize the speed of light c has reappeared in their formulae. This is another one of these weird numbers: for any object with constant velocity $v = \frac{1\,\text{bm}}{1\,\text{bs}}$, the mass of 1 bkg corresponds to a frequency of *exactly* $\frac{c \cdot 1\,\text{bkg} \cdot 1\,\frac{\text{bm}}{\text{bs}}}{h}$. The blobfish, therefore, throw various objects with a constant velocity through the ocean and measure the amount of distance the object covers in bm per bs, that is its velocity in blobfish units. With this velocity v, the blobfish calculate the frequency ν expected, if the object had a mass of exactly 1 bkg. They then let this object float into a de-Broglie wave-frequency measurement device, which has two slits and therefore was, creatively, named a two-slit experiment by the humans, to get out the frequency. The blobfish repeat this procedure until they measure a frequency of exactly $\frac{c \cdot 1\,\text{bkg} \cdot 1\,\frac{\text{bm}}{\text{bs}}}{h}$. The blobfish celebrate this, and the fact that they have performed their first quantum mechanical experiment, by wasting another 7 minutes brewing delicious coffee.

The blobfish are particularly pleased by the aesthetics of their blobfish-kilogram definition. Not only does it make use of the Planck constant h that seems much more general than the speed of (only) light and some frequency of someone's favourite element, but it also defines the frequency required as exactly 1, expressed in h and c, which feels both pleasing and natural to the blobfish. A small debate breaks out about this point during the coffee break. They soon realise that the speed of light is actually at least as fundamental: The humans just should have more accurately called it the «speed of any massless object in vacuum» or (the option the blobfish prefer) the «universe's speed-limit». And the caesium frequency actually depends on a rather intricate quantum mechanical phenomenon that the humans, by somewhat desperately trying to compare it to rotations of objects on human scales, called «coupling». And the blobfish find any quantum mechanics aesthetically pleasing.

Their discussion is ended by one blobfish's horrifying realisation: By defining their blobfish-units based on universal constants, the blobfish have also, by accident, *exactly* defined these constants. The Cs-frequency $\Delta\nu_{\text{Cs}}$, the speed of light c, the Planck constant all are now *defined* as an exact number and have *no* uncertainty. The speed of light c, for example, now simply corresponds to 1 bm per $\frac{1}{299792458}$ bs or 299792458 $\frac{\text{bm}}{\text{bs}}$ *exactly*, as stated in the instruction's original definition.

They also realise that they wasted something of an opportunity here. By defining the unit of velocity as $1\,c$ they could have saved themselves any of these strange numbers. Any velocity would then just be a fraction of the speed of light, a (very fast or very light) blobfish could for example swim at half the speed of light. In fact, they could have done this with all the universal constants of nature they have used, thus forming a «natural» system of units. Though they find this proposition very beautiful, the blobfish also do not want to brew their coffee for $7 \cdot \frac{9192631770}{\nu_{\text{Cs}}}$.

Current

Now that the blobfish have actually defined the units of time, length and mass, they return to their original idea and want to define the unit of voltage. They discover, however, that even though this unit turns out to be most useful in *measuring* things, the humans have not directly defined it through a universal constant. Instead, the blobfish must first define the unit of current — that is, charged objects in motion — which the humans (the blobfish guessed it) named after a human: ampere or 1 A. The blobfish discuss a new name, but ultimately decide to stick to ampere, because they find electrodynamics confusing, and do not want to complicate things any more. The definition, at least, is quite straightforward.

> The ampere is defined as the quantity of current of 1 coulomb per 1 second.

The blobfish are initially pleased by the seeming absence of any strange numbers, but fail to see the specific experiment — i.e., the specific universal constant — they should use for the definition. That is, until they realize that 1 coulomb, which they discover to be a bogus unit named after another (of course) human, actually corresponds to the charge of any elementary particle, that is for example an electron or a proton. This is the universal constant they were looking for, the elementary charge *e*. They further discover that charge comes in two flavours, either positive or negative, and that, depending on which flavour of charge is moving, the direction of the current changes. The humans have, to their discredit, probably made the worst imaginable mess out of this fact. Not only did they define the particle that is most often in motion — the electron — which is, therefore, the type of current most intuitive to humans, as the *less* intuitive «negative» charge. A problem that goes back to the first human to define the two flavours, Benjamin Franklin, who *wrongly* thought his positive particles were responsible for current and who, perhaps as punishment for his ignorance, did not get a unit named after himself. Even worse, the blobfish are made to understand by their guide that different groups of humans used different conventions to define the direction of current, going so far as using the same names to denote two exactly opposite things. This is why the blobfish think that electrodynamics is complicated.

The set-up needed by the blobfish, however, now becomes obvious. They simply need any particle with one elementary charge. They choose an electron for nostalgic reasons. An electron is also easy to procure: they simply get it from the same place they got their original ^{133}Cs-atom from. The blobfish shoot one such electron through a wire exactly once per second. This current, the stream of charge in motion, corresponds to exactly 1 A.

Temperature

After weighing coffee beans and measuring brewing time (and finally getting some exact current down to the bottom of the ocean to actually brew anything), the last missing component for the *exact* cup of blobfish coffee is to optimize the brewing temperature. Something the blobfish particularly struggle with, due to the high pressures at the bottom of the ocean. They now set up an experiment to define the unit of temperature 1 blob or 1 B. The guide instructs them to define a unit called kelvin, named after (what else) another human, but the blobfish decide to finally name a unit after themselves, given how hard they've worked to fix this disaster the humans left them with.

The blobfish are relieved to learn that temperature, just like length or mass, has an obvious 0-point. The blobfish know how handy such a 0-point is, as it makes comparisons between measurements directly possible. Two weights or two distances can be arbitrarily compared, 1 bkg or 1 bm are always the same. Comparing two watches is not always as straightforward: Let us assume two blobfish are tasked with timing the brewing of coffee by a third blobfish. After the brew, one blobfish might have measured 3 minutes while the other measured 4 minutes. This could be because the watches are imprecise, but even two perfect watches will show different results if the two blobfish started their timing at different points. One blobfish might have started the watch after the beans were ground, the other only when the water actually reached the boiling point. Neither one is wrong, they have simply set various times as the 0-point (either the grinding or the boiling). The blobfish debate whether a 0-point of time could be set at the beginning of the Universe, but the guide gives no instructions on how to measure this point — and some blobfish even doubt that such a point in time exists. The task of instituting a global watch body that makes sure all clocks give the same time of day, something that took up a good part of the budgets of the now defunct human meteorological institutes, is adjourned by the blobfish because they know no universal constant will get them out of this trouble.

The definition of the unit of temperature turns out to be quite straightforward and, fortunately for the blobfish, includes some more quantum mechanics. Their first task is to take any material (really, any collection of atoms at all) and cool it down until there is no more energy in the atoms[ii]. This is the 0-point of temperature because the material cannot be cooled down any further. Next, the blobfish need a source of energy. They simply use their frequency generator, because, as they now have found, frequency is directly proportional to an energy, see equation 9.1. The universal constant required in this case is the Boltzmann constant k_B, again a human. The Boltzmann constant defines (and is itself defined by) the energy required to change the temperature of any system by 1 B exactly. Temperature T and energy E are hence related by

$$E = k_B \cdot T. \qquad (9.3)$$

As always, the constant is also a strange number in this case, and the blobfish generate a frequency of *exactly* $1.380649 \cdot 10^{-23} 6.6207025 \cdot 10^{-34}$ s corresponding to the energy needed to go from 0 B to 1 B.

[ii] Again, something only blobfish can do, or would otherwise have to extrapolate.

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The blobfish also realize that the inverse is true as well: Any material with some temperature will emit waves of exactly the frequency that corresponds to the energy of this temperature. This type of radiation has nothing to do with the waves most objects irradiate as light — that is, colour — and so would even happen for objects that irradiate no light at all, whose colour hence would appear black. Sensibly, as the blobfish find, the humans named this phenomenon «black body radiation». Given that the blobfish can measure frequencies, they have an exact way to measure temperature as well.

Luminous Intensity

«The candela (cd) is the unit of luminous intensity», the guidebook lyrically proclaims. The blobfish are slightly befuddled by the meaning of the term «luminous intensity», which they do not find to be very universal (or even very useful) as a unit at all. They learn that it refers to the amount of light emitted by a light source in a certain direction. The blobfish then immediately look up the definition of «amount of light» or «wavelength-weighted power», as the guide generously corrects them, which refers to the amount of energy per time that a given light wave carries. The blobfish briefly discuss moving to the *very* bottom of the ocean and just universally defining the «luminous intensity» as zero. In light of logistical reasons, mainly the unresolved question of how to move their new and expensive espresso maker, they decide against it.

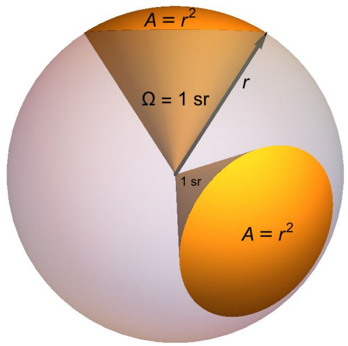

Abbildung 9.2: A solid angle refers to the area on the surface of a sphere enclosed by a particular angle. One steradian , or 1 sr, refers to the area that equals the square of the radius of the sphere.

The blobfish set out on their penultimate experiment, holding on to some grudge against their guidebook for making them undergo such a cumbersome procedure for such an ultimately useless unit. The universal constant defined is probably the strangest yet and corresponds to how many $\frac{\text{cd}\cdot\text{sr}}{\text{kgm}^2\text{s}^3}$ a frequency of $540 \cdot 10^{12}\,\text{bs}^{-1}$

has. This constant happens to be (or rather, is defined as) $683\frac{\text{cd}\cdot\text{sr}}{\text{kgm}^2\text{s}^3}$. The blobfish throw up their hands at figuring out how this definition came about — and suspect that even the nerds for which this unit was designed did not care too much about its definition.

They are further confused by the presence of a still undefined unit sr, which they learn stands for steradian , the unit for measuring solid angles. A solid angle of 1 sr corresponds to the area on the surface of a sphere that is equal to the square of the radius of this sphere. What a mouthful…even for our QM-loving blobfish. They thus set up a light source of exactly $540 \cdot 10^{12}\,\text{bs}^{-1}$, which they can check using their exact Cs-frequency. They then use a detector that exactly covers $1\,\text{bm}^2$ at a distance of 1 bm, or 1 sr, to measure the energy the light source emits[iii]. They then let the detector measure for exactly 1 bs.

The product of the frequency $540 \cdot 10^{12}\,\text{bs}^{-1}$ times this most strange constant $683\frac{\text{cd}\cdot\text{sr}}{\text{kgm}^2\text{s}^3}$ divided by the value the detector measured is *exactly* 1 cd. The blobfish immediately abandon this apparatus and never measure a luminous intensity again.

Amount

The last unit left to define is the unit of amount, which makes the blobfish chuckle a bit because there really is no need to define a *unit for counting*. The humans have done so nonetheless, by making use of another constant named after another (surely this must be the last one!) human, the Avogadro number N_A. It is a very strange number too, but makes a very specific operation very easy, which happens to be the reason for this unit in the first place. Because the unit of amount cannot be derived through any other units (unlike the unit of voltage, for example), it had to be defined. And because a very specific group of people (which happens to have been the same group of people responsible for the mess of defining the direction of current twice) used this very specific operation a very specifically large number of times per day, they insisted it be defined this way.

The unit of the amount is the mole, or 1 mol, with whose name the blobfish have no issue, given that it is (a) for once *not* named after any human and (b) becau-

[iii] For example, by letting the detector absorb all the energy that goes through this 1 sr from the light source and then measuring the frequency it emits (through black body radiation), which corresponds to the energy of the detector if multiplied by Boltzmann's constant k_B.

se it sounds a little bit like «molecules» for which the unit was actually defined. The very specific operation it simplifies is converting a mass of pure atoms into the number of atoms. The Avogadro-number $N_A = 6.02214076 \cdot 10^{23}\,\mathrm{mol}^{-1}$ is so defined that a particular trick works for this conversion: take the weight of your substance in $\frac{1}{1000}$ bkg or 1 bg and divide it by the number of protons and neutrons of your atom (ignore the electrons, because they essentially have no mass) to get the number of moles. A Cs-atom, as we know, has a total of 133 protons and neutrons. Thanks to the mol, we know that 133 bg of $^{133}\mathrm{Cs}$ corresponds to 1 mol of atoms. The genius of the mole is not that it makes counting more precise (as the blobfish have long learned from their Cs-clock, counting is *exact*) but that *you can count by weighing*. In fact, the conversion from gram to mole is so easy that blobfish (who are very good at arithmetic, as is probably obvious by now) can do it without a calculator[iv].

This concludes the blobfish's heroic endeavour. They have undertaken what is arguably one of the greatest projects humanity has ever embarked on: to define the units of all measurement universally, and without ever tapping into self-reference, such that they are conserved everywhere and in perpetuity throughout the universe. To be rediscovered (and slightly redefined) by any observer that wishes to do what we humans have done: *Putting numbers to things*. There is probably no single concept more influential in both our daily lives and the history of all human progress than the idea of *measurement*, and few things other than eating or breathing run back so far in our history (and so deep in the phylogenetic tree) as *counting*. The blobfish now, finally, are enjoying their cup of *exact* coffee, and, while discussing a series of quantum mechanical measurements they intend to perform in the future, they bemusedly admire these strange creatures, whose definitions were so instructive — if ultimately very, very *human*. Perhaps, in another 370 Million years or so, they will have once again evolved into an air-breathing, two-legged species obsessed with measuring the world just as *self-centred* and as *exact* as the one whose units they now inherit.

[iv]They of course still use one because who really trusts their head, if they can trust a calculator?