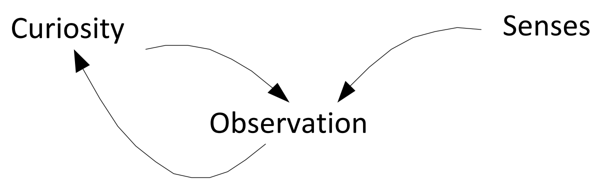
How Computers Work, Lecture 1
By Marc Clifton
The first of a series of lectures intended to be given in 2020
that was never publicly given due to COVID

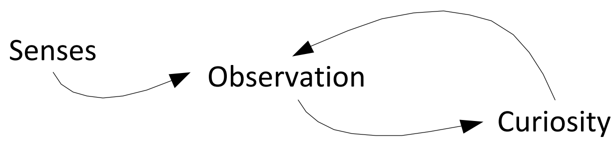
## Part I: Observation, Senses, Curiosity, and Science

*Understanding the science, thinking, and motivation that lead to the creation of your desktop computer, laptop, and phone is not just a history lesson. How your computer works reveals fundamental truths, near-truths, and non-truths about how the world works.*

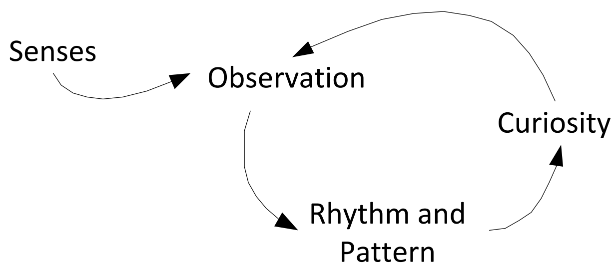
It certainly is not an original thought that human beings are curious creatures, and I don't just mean as "curiosities", but that we are innately curious about…everything. How do we satisfy our curiosity? Through observation!




But the opposite is perhaps more true – **our unique ability to observe our inner life and the outer world with our senses is what motivates our curiosity.**



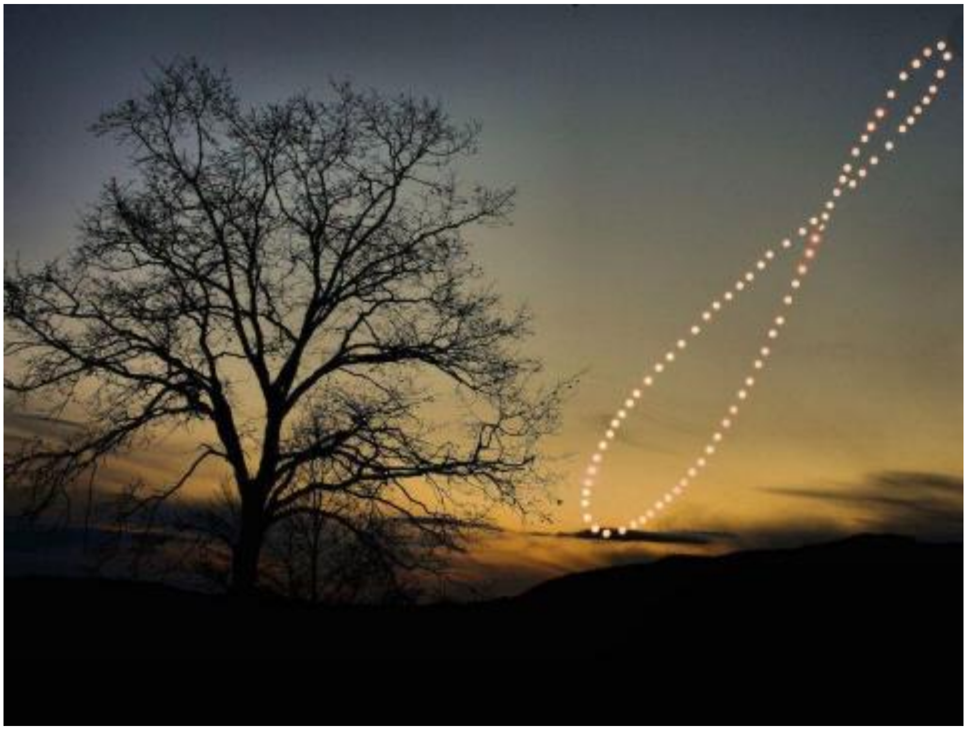

We have an amazing number of senses, and one of the first things we observe with these senses is the rhythm of our bodies and the universe.




The sun rises and sets, we wake, we sleep, we wake again. Our heart beats in a rhythmical pattern. The stars traverse the sky in cycles.

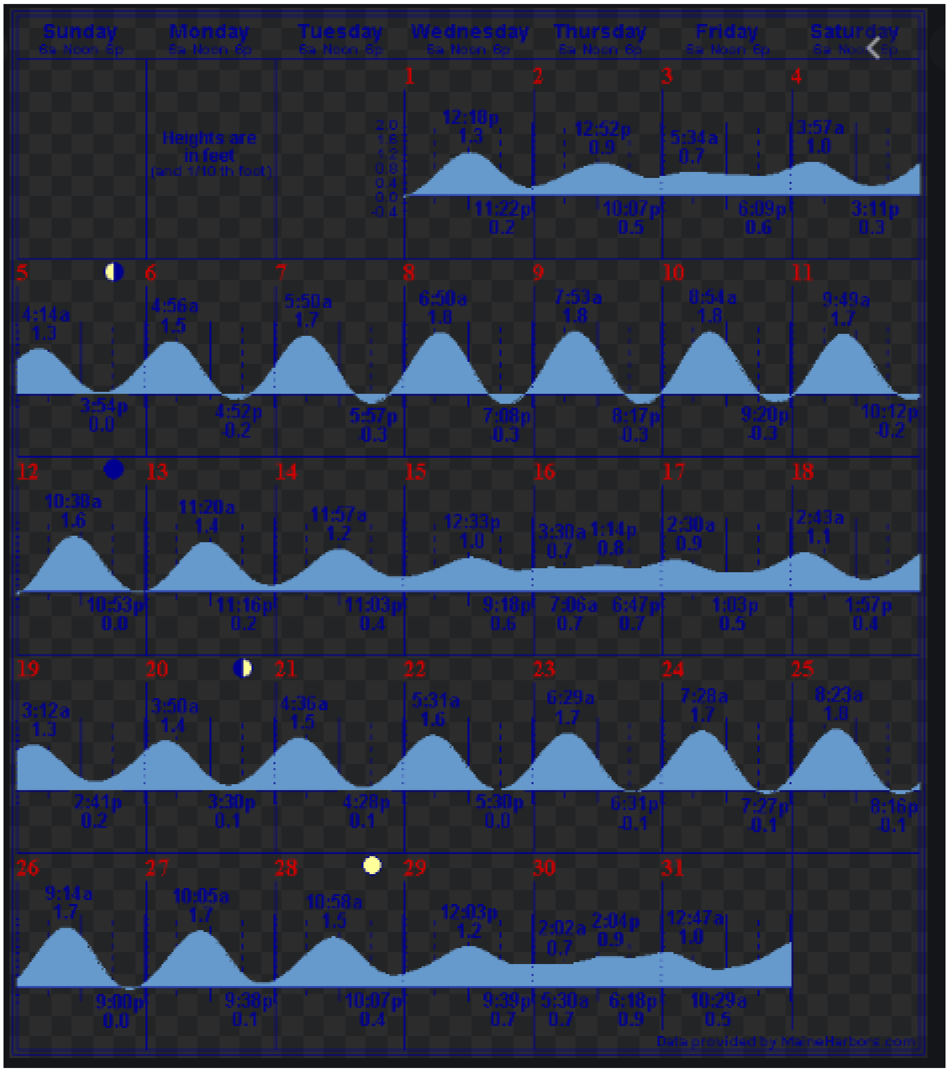
And closer observation reveals that these cycles are not that simple.  The sun rises and sets in a different point on the horizon each day, but in a giant lemniscate that becomes a “year.”

Figure 1: Sun at a constant time each morning



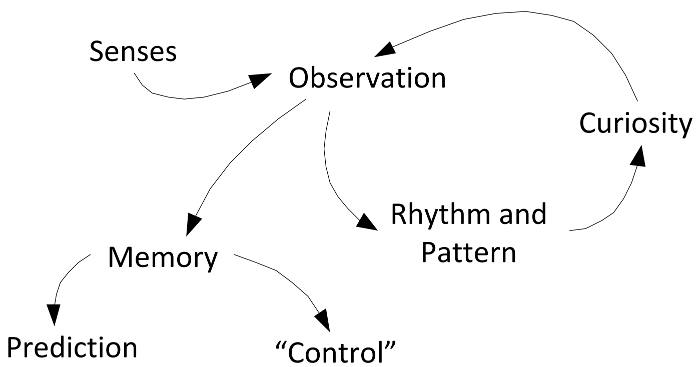
Tides wax and wane throughout the lunar month:

Figure 2: Tidal chart




**As we observe these cycles, another uniquely human quality comes into play – we cognitively (consciously) remember these cycles and realize that we can use them *to predict the future*.** Being able to predict the future gives us some semblance of control over our lives in the present *and to predict what our lives will be like in the future.* So we build instruments not just to validate our predictions but to plan our lives – when to plant seeds, when to harvest crops, when to marry, when to conceive a child, when to go to war and when to make peace.

Figure 3: Stonehenge, a very ancient instrument – 5000 years old -- for predicting the equinoxes, solstices, and possibly eclipses




**Our observational capabilities drive our curiosity which informs our understanding**, and with that newfound understanding we make refine our observational abilities, and this drives our curiosity even deeper.

It is one thing to be curious about the pattern of the sun, the moon, the tides, our sleep, etc. It is another thing to discover that these patterns are cyclic and that we can predict them (some more accurately than others!) **At some point our ability to observe the physical world encounters the boundaries of our senses.** As most of us have *at best* poor and inaccurate supersensible senses, our observation is relegated to what we call the physical world. Through the observation of the physical sense-able world we can come to a better understanding of the supersensible world -- that which we cannot see or explain through our senses or apparatuses. Here I am using the world supersensible in a non-spiritual sense because the concepts of dark matter and dark energy are not directly sense-able, not to mention subatomic particles like quarks which are inferred, rather than directly observed, through of how they decay into other particles that we indirectly observe as they collide with the detectors. Even the EM spectrum, light, radio waves, x-rays, etc., are not directly observable – we "see" the light and color because it interacts with our eyes or our mechanical sensors, but we do not, and neither our machines, "see" a wave or particle of "light" as it traverses space – so we can "scientifically" say that much of the universe is supersensible – it cannot be directly perceived by our physical senses or our machines.

**Yet, we can enhance our senses with devices** – whether this is the pair of glasses sitting on your nose, or a hearing aid, or perhaps the telescope on your deck or the X-ray machine the doctor uses to view a bone fracture or the ultrasound machine for early detection of tumors, to name a few such "devices."

## Part II: Everything is a Number

All of these devices have come about through the invention of mathematics.

*Mathematics (from Greek μάθημα máthēma, "knowledge, study, learning") includes the study of such topics as **quantity** (number theory), **structure** (algebra), **space** (geometry), and **change** (mathematical analysis). It has no generally accepted definition.*

***Mathematicians seek and use patterns to formulate new conjectures; they resolve the truth or falsity of conjectures by mathematical proof**. When mathematical structures are good models of real phenomena, mathematical reasoning can be used to provide insight or predictions about nature. Through the use of abstraction and logic, mathematics developed from counting, calculation, measurement, and the systematic study of the shapes and motions of physical objects. Practical mathematics has been a human activity from as far back as written records exist.*( https://en.wikipedia.org/wiki/Mathematics)

The "invention of mathematics" is actually a humanly egoistic way of saying that "people invented a way of expressing what the universe does innately." It's like discovering an amazing truth that has always existed but not having the language to communicate that discovery. Sound familiar? [Steiner often pointed out that the language for communicating supersensible perception simply does not exist.] That is one way of looking at what "the invention of mathematics" means – **it is the invention of a language to communicate the discoveries we make regarding the innate truths about the universe**.

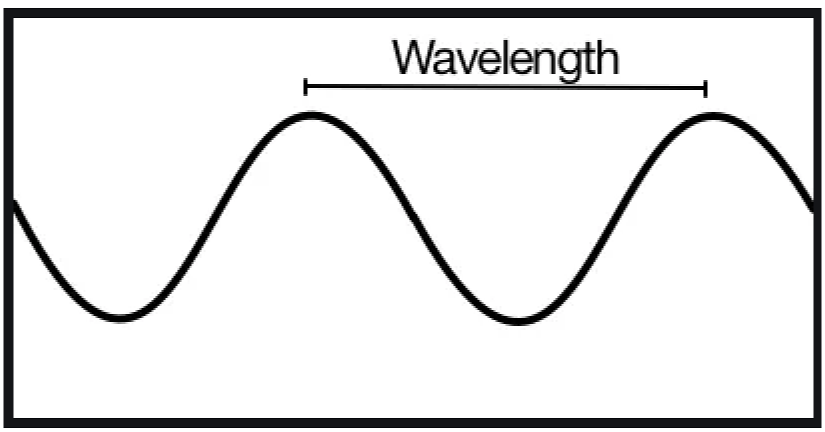
So your eyeglasses is math applied in the discipline of optics. A hearing aid is math applied to the discipline of acoustics. Etc.

What is fundamental about almost everything observable, whether it is quantity, structure, space, or change? **That fundamental thing is that almost everything can be expressed as a number.**

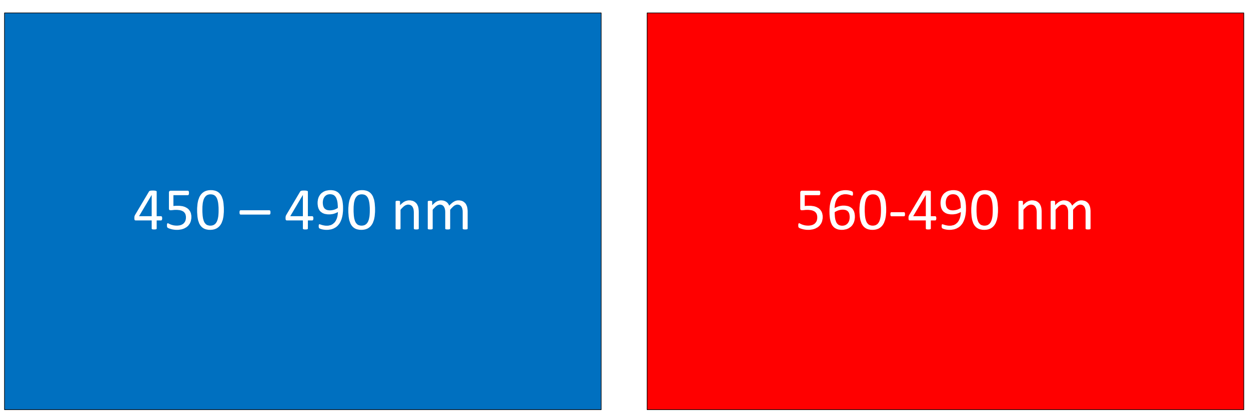
Unfortunately we strive to remove that key word "almost" out of the previous sentence. This has affected every scientific discipline and religious belief system – to reduce everything, and I mean absolutely everything, to a number, from your brain chemistry to your test scores to the number of angels that can dance on a pin to the actual age of the universe -- science tells us one thing, a detailed analysis of the Bible by some people gives a very different number.

**Once something becomes a number, we gain understanding and we risk the loss of the mystery.** A rainbow is no longer the mystery of God's covenant with man but rather a set of equations describing the prismatic effect of water droplets on light. **And yet the irony is that the more we reduce the world to the materialistic dullness of numbers, the more mystery is revealed!** To paraphrase Aslan, "the White Witch knew the magic from the beginning of the world, but she did not know about the deeper magic from before the beginning." And so it is with numbers – we learn something by reducing that thing to numbers, and then discover there is something even deeper that resurrects our wonderment.

Light can be reduced to two numbers: frequency and amplitude. The frequency tells you the color of the light (99% of the light spectrum is outside of the visible spectrum your eye can sense.) Amplitude tells us how bright the light is.




Blue is a wave where the wave length (ie wavelength) is between 450 and 490 nanometers. Red has a wavelength of 560 to 490 nanometers:



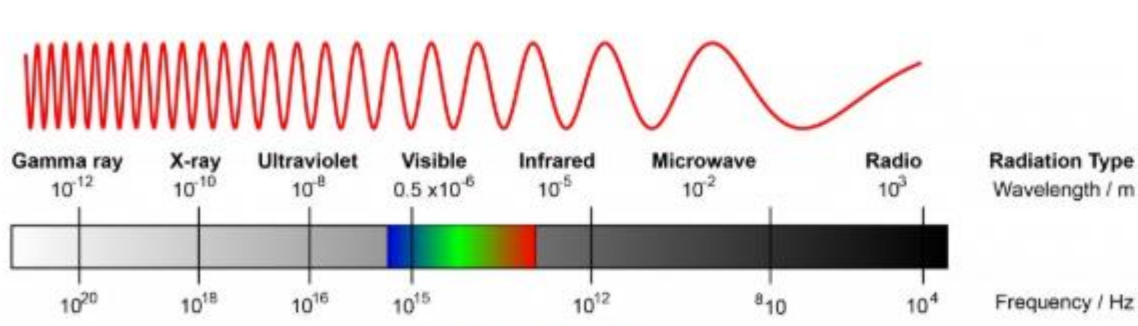



Image: InductiveLoad (CC-BY)

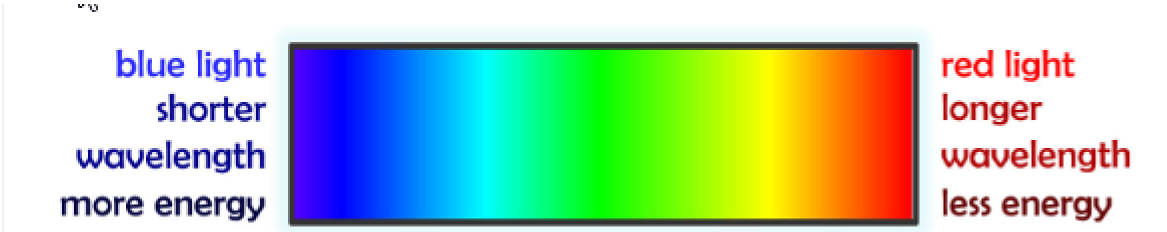
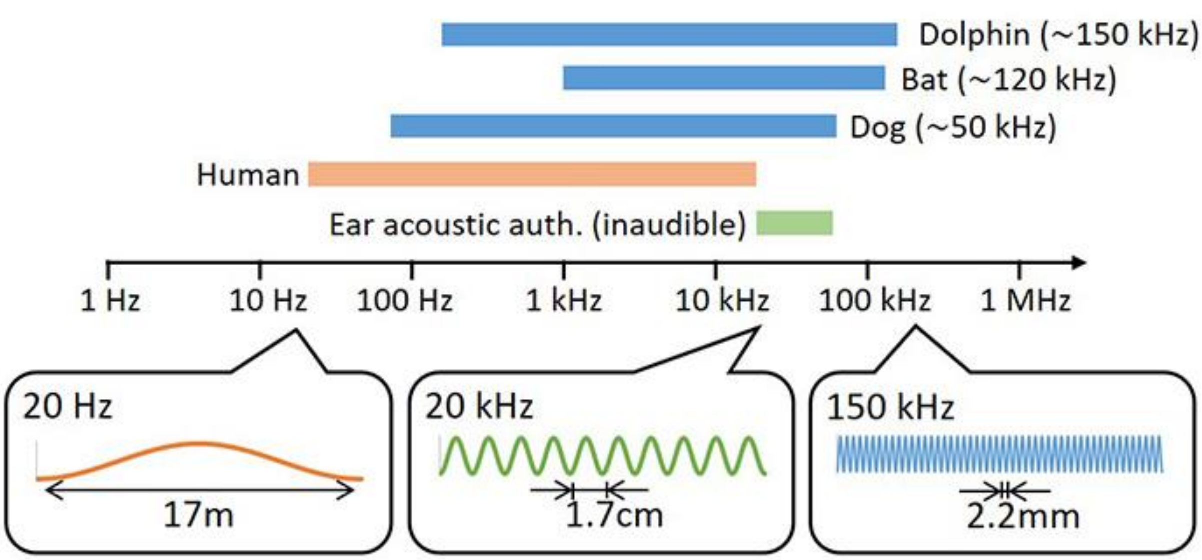



Image: science made simple (CC-BY-NC)

Sound – frequency and amplitude. Again our hearing sense is limited – we cannot hear the ultrasonic pings of bats nor the subsonic communication of elephants as they flap their giant ears.




Temperature, humidity, pressure, velocity, mass (and therefore weight), distance, time, texture, everything physical can (and often with great accurately) be reduced to a number. Non-physical things can be reduced to a number. On a scale of 1 to 10, how much do you love me? When you taste this food, rate its five modalities: saltiness, sourness, sweetness, bitterness, and savoriness (aka "umami".) We have scientific experiments to thank for reducing taste into these 5 modalities, which is ironic because taste is also closely coupled with smell and some people would even say with texture, warmth, wetness, and so forth.

Clearly many of these "reduction to a number" processes work, and work very well, whether we use them consciously (flying a spacecraft by Pluto) or unconsciously (driving to this talk relied on many, many mathematical truths about the universe.) Most importantly, math, and the underlying "number-ness" of the world, creates a consistent, sane, **shared and shareable** experience of life.

Q: What things cannot be expressed easily as numbers?

**The other limitation of our senses, or more precisely, our entire sense organism, is the ability to process certain kinds of information very quickly and with repeatable accuracy.**

We learn as a child how to catch a ball that is thrown to us. We hopefully learn to throw a ball so that the other person can catch it! The equation for the trajectory (or arc) of that ball on the playground is quite trivial:

$x = Vx * t.$

$y = h + Vy * t - g * t^2 / 2.$

And can be derived by making very accurate observations. Our sense organism (as in, our entire perceptive system) is involved in the ability to throw a ball so it can be caught – we are aware of what the ball weighs in our hand, how much motion we are putting into our arm, the moment we want to release the ball and our entire body position at that moment, even how the ball rolls off our hand as we put spin on it. Doing this accurately over and over again, well, if that were possible, every baseball pitch would be a strike.

Conversely, if we want to perform this calculation to lob a cannonball from our current position across a field to strike the enemy, it takes so long to do the math for this that the enemy has very likely run across the field and captured us. And you probably would make mistakes in the math as well, especially given the high pressure situation!

And hence we come to ENIAC, the first general purpose digital computer:

*Although ENIAC was designed and primarily used to calculate artillery firing tables for the United States Army's Ballistic Research Laboratory (which later became a part of the Army Research Laboratory), its first program was a study of the feasibility of the thermonuclear weapon. (*[https://en.wikipedia.org/wiki/ENIAC](https://en.wikipedia.org/wiki/ENIAC))

## Part III: Analog vs. Digital

The simplest way to describe analog vs. digital is this:

Analog: the volume knob on your old stereo

Digital: a light switch

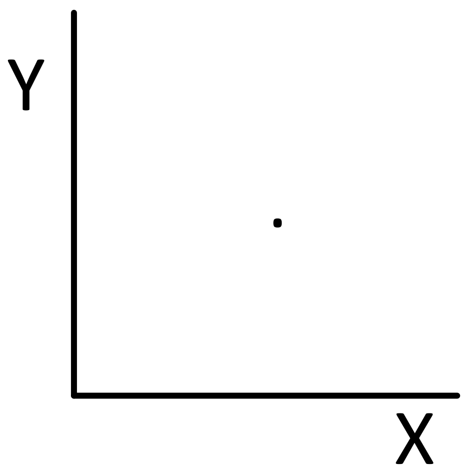
But let's deepen our understanding of the difference between analog and digital.

Given a line: -------------------------------

Let's say the line starts at 0 and ends at 1.  Give me some numbers that are between 0 and 1. One half, 2/3, ¼, ¾, etc.  How many numbers are there on this line that are between 0 and 1? **There are an infinite number of numbers!** That is what analog means – it is a "number" amongst an infinite number of numbers.

Let's draw a vertical line.

Now we have an "analog space."  If I put a point in that space, there is a pair of numbers (x,y) that precisely describes where that point is in the box.

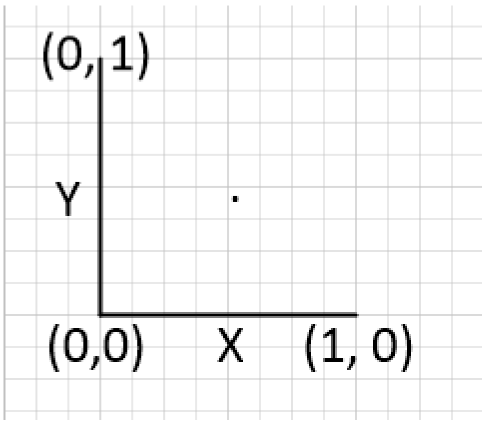



But can you tell me what that pair of numbers is?  No – **the problem with "analog" is that while it is precise, it is impossible to communicate that precision.**  You could never communicate *precisely* the coordinate of that point because the "number", expressed with the digits 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9, is itself infinite in length.  There are exceptions of course. The four corners: (0, 0), (0, 1), (1, 0), (1, 1).  Or the center (½,  ½), but given that the box has an *infinite number of points,* there are an infinite number of numbers that you cannot precisely communicate.

Q: What are numbers that you know that "go on forever?"

However, you can "approximate" the coordinates for that point.  **Digital is an approximation so the number of digits needed to describe a point on a line or in space is *finite*.**

So if superimpose a grid:

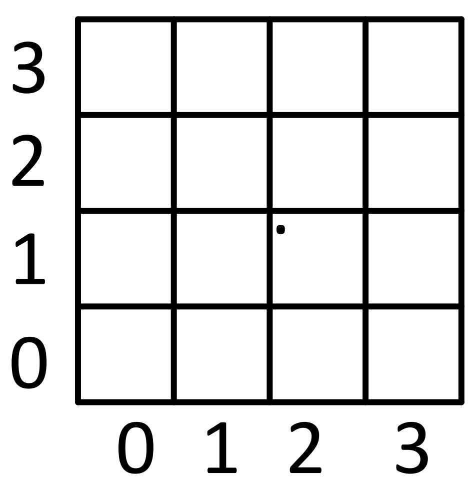



We can say that the point is around X=0.42 and Y=0.37.  But this is an approximation!

**With digital, we lose precision but we gain the ability to communicate!** We do this all the time!  How tall am I?  I'm 6 foot 3.  That is a digital approximation of a number that is otherwise impossible to communicate precisely!  What is the temperature outside?  It's 45 degrees outside – that's another digital approximation of a very "analog" quantity!  Even when we say "this color is blue", we are performing a digital approximation by fitting a word, "blue", into our concept of a range of light frequency that looks like blue.

**The fancy term for this "digital approximation" is called "quantization" – reducing something infinite into discrete "quanta", or "packets."**

For example, we can impose a grid on our space of infinite points – let's say a 4x4 grid.  Now we can precisely communicate the grid coordinates in which our point "approximately" resides.  We have reduced infinity to 16 "quantized" coordinates.




Using this grid, we could say that our point is in grid (2, 1).  But look at all the possible (actually infinite) points that can actually be in that cell.

**This gives you a glimpse of how "the digital world" is a not-quite-true representation of the real world.** It is very important to understand this concept of quantization and how it can lead to gross inaccuracies about world. Yet at the same time, because it makes communication of the world possible, it allows us to discuss the world and deepen our understanding of it.

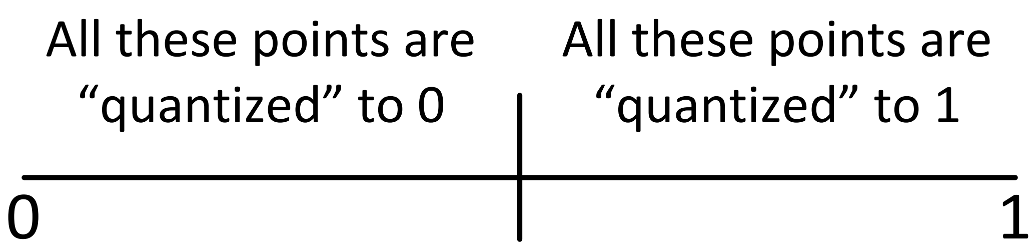
**Because science strives for precision, but communication requires quantization and therefore results in imprecision, you can see how there is this inborn tension that science is always struggling to manage.**

What becomes ever increasingly important therefore is to communicate with language (whether words or numbers or other expressions of language) as precisely as possible the "imprecision" of what we are trying to communicate!

## Part IV – Why Binary

Let's look at the line again. The simplest quantization of that line is "0" and "1".

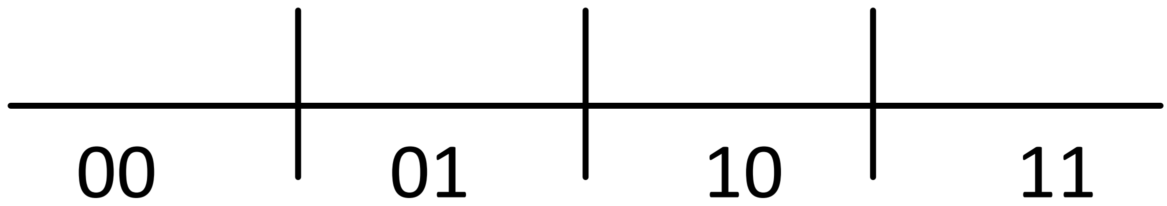

Any point between 0 and ½ is quantized to 0, and point between ½ and 1 is quantized to 1.



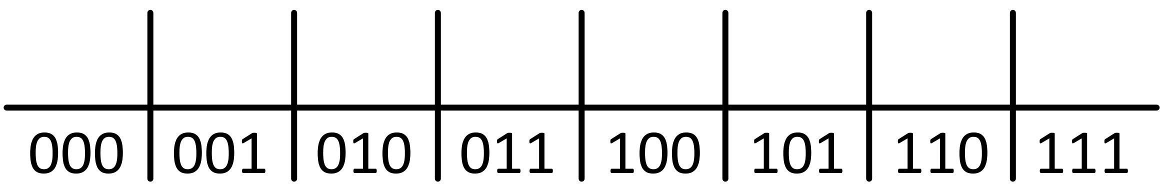

Not very accurate, is it? But this is what a single "bit" is – the quantization of something into a 0 or 1. Now, we do not want a "bit" to be able to represent say, 3 states, 0, ½, and 1, because if we continue that progression, we're back to where we started, trying to represent all the possible states of a number, and the result is that we can no longer communicate.

So what do we do instead? We add more bits!

If we have 2 bits, we now have four states: 0-0, 0-1, 1-0, and 1-1. So now those four bits can quantize to four regions on the line:



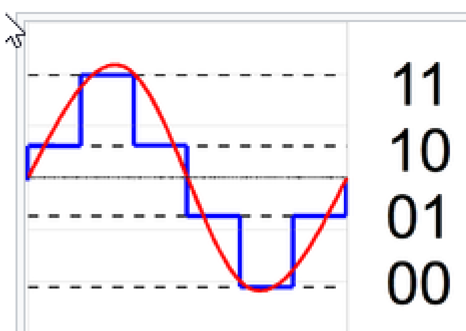

If we have 3 bits, we can quantize to 8 regions on the line and we have increased the “precision” in which we can communicate the “location” of a point on that line.



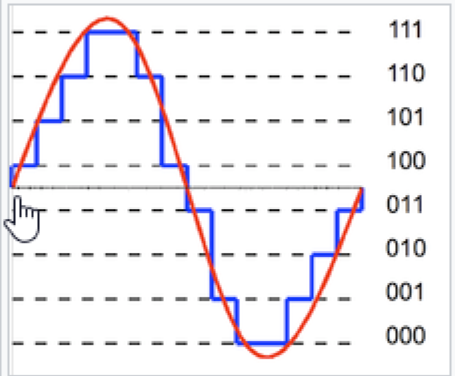

The “depth” of our quantization is 2 to the power of the number of bits.  So if we have 8 bits, we have 256 discrete quantization states.  16 bits – 65536 states.

**The more bits you have, the more accurately you can communicate the analog infinitely impossible representation of something about yourself or the universe, albeit with some loss of precision.**

For example, a sound wave is quantized in time and amplitude:




2-bit resolution with four levels of quantization compared to analog.[3]



3-bit resolution with eight levels.

This is how a CD player works as well as the DVD movie.  The more bits we use and the faster we “output” those bits, the better the sound or video quality appears to our ears and eyes.

ASIDE: Now here’s another interesting thing about the digital world – it can be “compressed.”  Compression means that it takes less space to store the numbers, and compression can either be “lossless” (you can “decompress” back to exactly the original numbers) or “lossy”.  With lossy compression, while it takes up even less space compressed, when you reverse the process, you do not get back the exact original numbers.  Audio and video compression is lossy, which is why when you look closely at a movie on a DVD, say with a scene of sky, the color has this “gradation” to it – it’s not a smooth shade from say, light blue to dark blue, even though your computer screen can do a lot better!

Amazingly, the universe has provided the means to physically, and quite easily, represent a “bit”, the state of either 0 or 1.  That is what a transistor does – a device made from silicon, germanium, gallium arsenide, and silicon carbide – earth minerals.

ASIDE: There are transistors that function in an analog way as well, and are used in many applications, particularly in converting a digital number (something represented by more than 1 bit) back to its analog analogue, such as sound and light.

## Fractions

So far we’ve really only looked at bits that represent whole numbers: 0, 1, 2, 3, etc.  But of course we need to represent fractions as well.

One of the simplest ways of expressing a fraction is to say that the bits to the right of the decimal point are each powers of 2 to the *negative* bit position:

0.1 = 1/2

0.01 = ¼

0.001 = 1/8

We can combine these bits, so:

0.11 = ¾ (1/2 + ¼)

But how do we represent something like 2/3, which in our decimal system is 0.666666…

It would look somewhat like this:

0.101011

Which would be 1/2 + 1/8 + 1/32 + 1/64 which equals, oops, 0.671875

You can see that binary is not really a good means of representing fractional numbers – they introduce an approximation on top of an approximation!

Here's another great example.  What's 0.2 + 0.1?  Obviously 0.3!  But look what Javascript, a popular programming language, says:

```
0.2 + 0.1
0.30000000000000004
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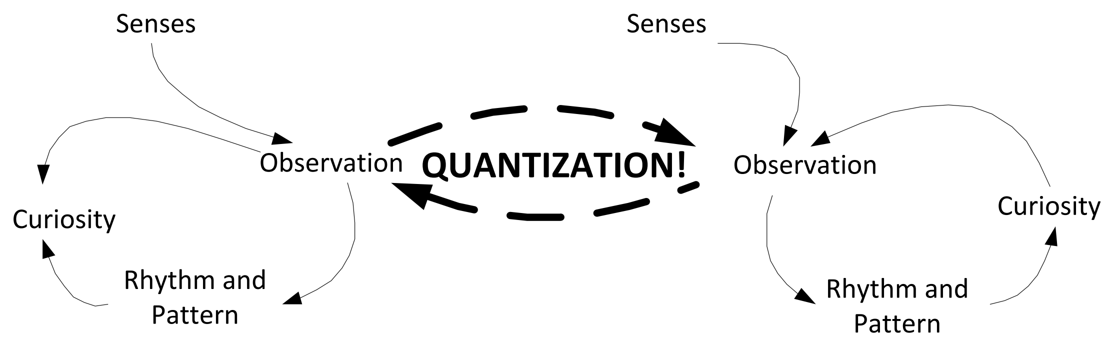
### In Summary

Let’s go back to one of the first drawings about observation and add another “person”, the person you to which you want to communicate your observation:




Any time we’re communicating between ourselves, we are quantizing the information so that communication is possible.

This quantization (generalization, imprecision, etc) is fundamentally at the core of the processes of how a computer works *in relationship* with the things we task the computer to do. The quantization of the richness of the analog world into a digital representation is ideally suited for the computer to then “number crunch” and spit out a new digital number.

Much as we may want to deny it, we, as people, are necessary bridge between the infinite (analog) world and the quantized digital representation of that world. If it were not so, we would not be able to communicate with each other. Computers live entirely in the digital realm, but we will see in future lectures how “sensors” let the computer step into the analog world as well.