Moore's Law and Space Exploration: New Insights and Next Steps

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Abstract

Understanding how technology changes over time is important for industry, science, and government policy. Empirical examination of the capability of technologies across various domains reveals that they often progress at an exponential rate. In addition, mathematical models of technological development have proven successful in deepening our understanding. One area that has not been shown to demonstrate exponential trends, until recently, has been space travel.

This paper will present plots illustrating trends in the mean lifespan of satellites whose lifespans ended in a given year. Our study identifies both Wright's law and Moore's law regressions. For the Moore's law regression, we found a doubling time of approximately 15 years. For Wright's law we can see an approximate doubling of lifespan with every doubling of accumulated launches. We conclude by presenting a conundrum generated by the use of Moore's law that is the subject of ongoing research.

Introduction

It has been observed that the rates of increase of technological capability in a variety of domains often follow exponential trends. For such domains there is a fairly predictable time constant at which the capability of the technology doubles although the time constants themselves vary quite a bit across domains (Magee *et al*. 2014). These trends are exponential and often described as conforming to "Moore's law," which originally described how the number of components that can be built into an integrated circuit doubles approximately every 18 months (Moore 1965).

But what causes these exponential patterns? Some noteworthy research done in this area suggests that this exponential progress is due to innovators applying lessons and principles from one domain to another domain (Basnet and Magee 2016; Arthur and Polak 2006; Axtell *et al.* 2013). The newly generated ideas will then be available for use in another domain and so on. The complexity of the technological system itself as well as functional requirements of the system influence how quickly the technology can be improved and leads to differing rates of progress (McNerny *et al*. 2011; Basnet and Magee 2016; Basnet and Magee 2017).

Another important description of technological progress was discovered by the engineer Theodore Paul Wright. This principle, known as "Wright's law," describes how as the volume produced of a manufactured good increases, the per-unit cost of the good falls at a predictable rate (Wright 1936). While Wright's law has important implications for operations management and business strategy it has also proven useful for technology foresight. An influential report indicates an equivalence between Wright's law and Moore's law when volume produced increases exponentially over time (Sahal 1979). A study in 2013 further compared Moore's law and Wright's law (Nagy *et al*. 2013).

While such patterns have been observed for fields as diverse as genome sequencing, LEDs, and 3D printing, they have not been observed for space travel. In fact, it is widely held that progress in space travel "has stalled" (Hicks 2015). A primary focus of our research program has been to determine if we are in a "space winter" or if there are in fact exponential trends to be found (Berleant *et al*. 2017).

The question of how to measure progress is not an easy one to answer. In fact, the wrong choice of metric may obscure the fact that space travel is improving (Roberts 2011). Cost may show an improvement trend, but collecting and analyzing the required data has proven non-trivial. As an alternative approach, evidence has been found suggesting an exponential trend with regards to spacecraft lifespan (Berleant *et al*. 2019). A key question (Nagy *et al.* 2013) has been whether this trend best fits a Moore's law-like pattern (improvement with respect to time) or a Wright's law-like pattern (improvement with respect to accumulated production volume).

One reason given for the apparent lackluster progress of space technology is the lack of commercialization. Matt Ridley in his book *The Rational Optimist* and others make the case that financial incentives play an important role in the development of any technology. From British capital markets during the industrial revolution to venture capitalists on Sandhill Road in Silicon Valley, history gives us good reason to believe that the expectation of profit is a strong driver of technological progress. Satellite technology represents the most commercialized aspect of space technology today. For this reason, we hypothesized that a data analysis of satellite technology may provide indications of exponential trending.

Analysis of Satellite Data

Figure 1 shows the mean lifespan of all satellites whose lifespans ended in a given year. A more detailed discussion of the data appears in Berleant *et al*. (2019), while here we emphasize those aspects most salient to (1) the focus of the present article, and (2) those elements of Figure 1 that represent an advance on the analogous figure in Berleant *et al*. (2019). The Moore's law regression is provided in equation (1) and the Wright's law regression is provided in equation (8). The top curve, Annual Count, shows the number of satellites whose lifespans ended (not launched) in the year given on the x-axis.

Both the Wright's law and Moore's law regressions show a general upward trajectory. Wright's law displays some irregular variations when plotted with respect to time, which is to be expected since Wright's law defines volume produced as the independent variable and not the x-axis variable, passage of time. If the x-axis showed volume instead, the regression curve would be free of such variations (but the Moore regression would then have them). For the Moore's law regression we have a doubling time of approximately 15 years. For Wright's law we can see an approximate doubling of lifespan with every doubling of accumulated launches.

Some of the earliest years were discarded from both regressions due to their inclusion leading to a poor fit to the regression curves. While this may seem contrary to the point of doing a regression it is useful for maintaining the ability of the model to predict, when early data is outlying or seemingly anomalous, and the primary interest is in extrapolating to the future. In this case, early launches were not representative of satellite technology as a whole and later data is more relevant than earlier data for the purpose of making predictions.

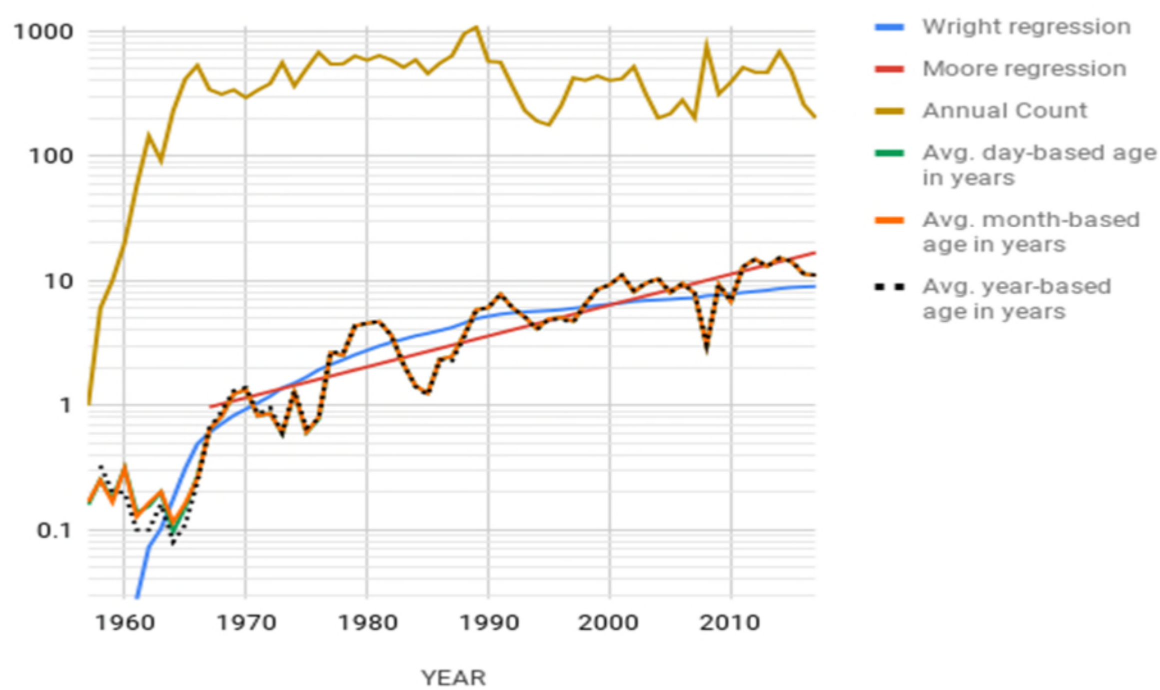


Figure 1. Annual count (top curve) and average age of satellites ending their lifespans each year.

An important question for measuring spacecraft lifespans is the correct unit of time to use. Lifespans were measured in days, months, and years (and then normalized so they could be directly compared) to examine how much using years and months distorted the graphs compared to more precise measurements in days. From Figure 1 it appears that years is not as good as months or days which are nearly identical. This occurs because measuring lifespan using years consists of subtracting the launch year from the end year. For example, suppose that a satellite was launched in December of 2016 and stopped functioning in March of 2017. Using years to measure this satellite's lifespan would give us a value of one year when in fact it had a lifespan of only three months.

End year was chosen rather than launch year because recently launched satellites would often still be in orbit, with only the shortest lived of them therefore contributing lifespan data for recent years, skewing the results and preventing a meaningful analysis.

Figure 2 illustrates an example of this phenomenon with lifespan data for spacecraft sent on deep space missions. When measured with respect to launch year we see that average lifespan increases until approximately 2000 and then decreases afterward, as significant numbers of craft launched in post-2000 years are still operational. This is because only short-lived spacecraft from this period are measured because these shorter-lived are the ones whose lifespans are available, leading to the noticeable decline in average lifespan due to the biased data, beginning in approximately 2000 and continuing to the present.

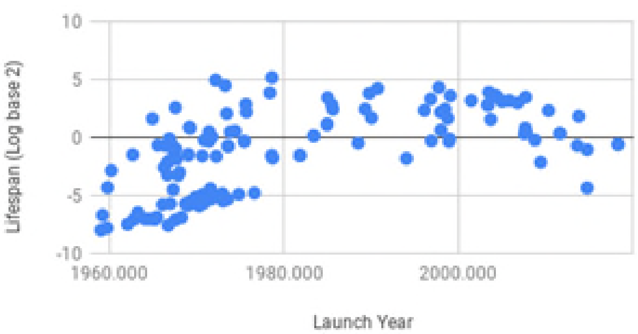


Figure 2. Lifespan vs. launch year for deep space craft.

The Moore's law conundrums

When comparing the RMS error of the Moore and Wright regressions it initially appears that Wright's law has a slightly better fit (Berleant *et al*. 2019). However, Wright's law may be more useful for another reason as well which isn't so obvious. While choosing the end year rather than start year made the analysis more feasible by removing the bias problem mentioned earlier, it also introduced another problem. If the observed doubling in satellite lifespan continues to hold then we must eventually reach a point where lifespan is increasing faster than the passage of time. This would require satellites dying in later years to be launched before satellites dying in earlier years, a seeming contradiction. Eventually we would reach a year for which satellite lifespans ending in that year would be predicted to be longer than the entire history of satellite technology. Since this scenario clearly makes no sense it remains an open problem of how it should be handled. Some progress is explained next.

If we still wish to associate lifespans with end year, when will Moore's law lose its predictive power? For this analysis let Moore's law be defined as:

$$y = a * 2^{\frac{(x-1957)}{b}} \tag{1}$$

where a and b are function parameters and x represents time and is used to model the current end year. Parameters a and b are set to 0.549 and 12.17 respectively since this minimizes RMS error (Berleant *et al*. 2019). The input value x represents end year and the value y is expected lifespan. The first year against which lifespans can be measured is 1957 since that is the year the first satellite was launched, this value is subtracted from x and only positive values are considered. For this reason, the historical time span y of satellite technology at year x is:

$$y = x - 1957 \tag{2}$$

In order to determine when Moore's law breaks down, we need to determine when the rate that lifespan increases with respect to time equals (immediately following which it will exceed) the rate that time increases with respect to time. In order to do this, we can solve (1) and (2) simultaneously, take the first order derivative and determine the year the two expressions are equal to one another.

$$0.549 * 2^{\frac{(x-1957)}{12.17}} = x - 1957 \tag{3}$$

Moving both expressions to one side:

$$0.549 * 2^{\frac{(x-1957)}{12.17}} - x + 1957 = 0. \tag{4}$$

Taking the derivative of the expression:

$$\frac{d}{dx}0.549 * 2^{\frac{(x-1957)}{12.17}} - \frac{d}{dx}x + \frac{d}{dx}1957 = 0 \tag{5}$$

$$0.549\left[\frac{1}{12.17}*\ln(2)*2^{\frac{(x-1957)}{12.17}}\right]-1 = 0. \qquad (6)$$

If we simplify and solve for *x* we obtain:

$$x = 12.17 * log_2\left(\frac{12.17}{0.549*\ln(2)}\right) + 1957 = 2017.84. \qquad (7)$$

Thus 2017 was the year that lifespans of satellites dying in a given year are predicted to begin increasing faster than the passage of time, a conundrum. What about the point where satellite lifespan is predicted to be greater than the length of the history of satellite technology? If we graph both equations (1) and (2), we can visually observe the points at which they intersect and thus the year that this predicted event might occur. Doing this shows that this point is reached in the year 2046 when average satellite lifespan is predicted to be approximately 89 years, and thus launched prior to 1957, when Sputnik became the first artificial satellite (Figure 3).

So, returning to the earlier point on which law is better for predicting future satellite lifespans based on year of death, Wright's law seems superior simply because (1) Moore's law based on lifespan as a function of end year began failing in principle in 2017 and will reach an even greater level of impossibility in 2046; and (2) launch year cannot work for recent years for which longer-lived craft are still operational.

Discussion

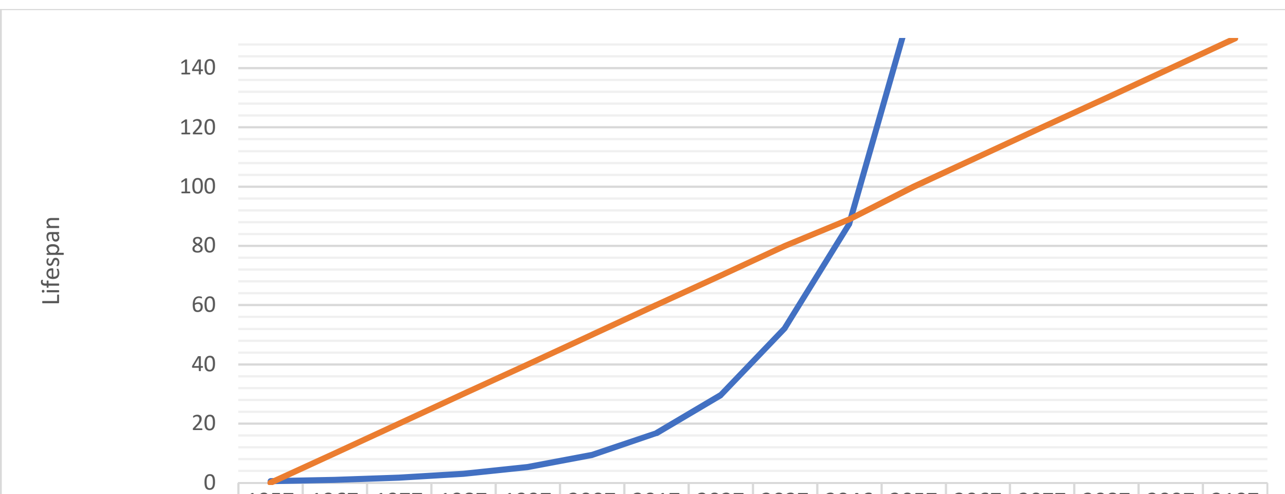
The Moore's law regression was described earlier in equation (1). The simple regression equation for Wright's law is as follows:

$$y = 0.0002446*ordinality^{1.04} \qquad (8)$$

Where *y* is the average lifespan for satellites ending in that year and *ordinality* is determined by the number of satellites ending in that year and previous years. Our preliminary research suggests that the conundrum associated with Moore's law that was described previously may also apply to the Wright's law regression, although at a much later year, in which case a Wright's law model would not form a principled alternative to a Moore's law model in the case of lifespan as a function of end year. However, this remains to be fully investigated.

Conclusions

It may appear that satellite technology has been progressing in an approximately exponential way, perhaps a little less vigorously than a Moore's law



	1957	1967	1977	1987	1997	2007	2017	2027	2037	2046	2057	2067	2077	2087	2097	2107
Moore's law	0.549	0.97	1.715	3.031	5.358	9.47	16.74	29.58	52.29	87.3	163.3	288.7	510.3	901.9	1594	2818
Time	0	10	20	30	40	50	60	70	80	89	100	110	120	130	140	150

Figure 3. Satellite lifespan vs. passage of time, showing a Moore's law crossover

model, but a little more vigorously than a Wright's law model (Figure 1). However, we can confidently predict based on the mathematical deduction presented earlier that the data in coming years must soon break decisively from the Moore's law trend line of Figure 1 and show that lifespan will soon not fit an exponential function of satellite year of death. Importantly however, we have certainly not ruled out the possibility of an exponential trend for some characteristic other than lifespan as a function of year of satellite death.

We plan to empirically verify the analysis we have introduced here against future satellites. Future research is needed to circumvent this mathematical problem and accurately identifying the degree to which space travel is an accelerating technology.

Finally, we close by pointing out that key results presented here should also apply to lifespans of other engineered artifacts besides satellites

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