

Steps toward Quantifying Advancement in Space Exploration

Chelsea HALL, Department of Information Science, University of Arkansas at Little Rock,
Little Rock, AR 72204 USA

Daniel BERLEANT, Department of Information Science, University of Arkansas at Little Rock,
Little Rock, AR 72204 USA

Richard SEGALL, Department of Computer & Information Technology, Arkansas State University,
State University, AR 72467 USA

Shen LU, Department of Computer Science & Engineering, University of South Florida,
Tampa, FL 33620 USA

ABSTRACT

The purpose of this paper is to present a brief summary of preliminary research performed by the authors on project with objective of developing a group of simplistic models and metrics for measuring performance of success of projects of NASA. A starting point of this is to review related work by others for other applications such as Moore's Law for different types of advances in technology. The cover article (Denning & Lewis, 2017) of this year's issue of *Communications of ACM* indicates that this is research of continuing interest.

Keywords: Space Exploration, NASA, Moore's Law, Wright's Law, Metric

1. BACKGROUND

A significant body of work has appeared in which advancement in various domains of technology has been characterized using equations to describe the trajectory of advancement. These equations give curves that match past data about the performance of a technological domain, with the intent of using them to then predict future advances in performance as well. Equations with names like Moore's Law, Wright's Law, and various others have been proposed and researchers have investigated which equations work best and what the parameters of these equations, or

laws, are for different domains of technology (Basnet & Magee, 2016a).

While important, such research leaves open the question of the mechanism behind the technological advances that they attempt to describe. In this paper, a mechanism is hypothesized. The key characteristic of the proposed mechanism is that technological advancement involves an interplay between scientific discoveries, which they attempt to quantize as UOUs (Units Of Understanding), and engineering component, subsystem, and system designs, which they similarly attempt to quantize as IOIs (Individual Operating Ideas). Thus, science and engineering are both considered key and their interaction leads to advancement in any given technological domain. The obvious question is whether a model of how and why technologies advance can help explain variations across different technological domains (Basnet & Magee, 2016b).

Magee et al. (2015) presented quantitative empirical trends in technical performance by addressing the issue of performance trends and patent output over time for 28 technical domains with the conclusion that Moore's law is a better description of longer-term technological change when the performance data came from various designs whereas

experience curves may be more relevant when a singular design in a given factory is considered. Statistical basis for predicting technological progress was presented by Nagy et al. (2013), and Combination-driven models of technological innovations networks was investigated by Sole et al. (2016).

1.1 Wright's Law

The classic paper by Wright (1936) is the origin of Wright's law of technological advancement. The author, Theodore Paul Wright, is a distinguished aviation figure, though not related to aviation pioneers Wilbur and Orville Wright. He did, however, win the Wright Brothers Medal in 1930 and also worked for the Curtiss-Wright Corp., named after its precursor companies Wright Aeronautical, associated with the Wright brothers, and Curtiss Aeroplane and Motor Company, associated with Glenn Curtiss. (This is an odd postscript to a feud between the Wright brothers, Glenn Curtiss, and the Smithsonian Institution over the invention of the airplane).

Wright (1936) discusses a number of curves and mechanisms relating to airplane manufacturing cost. It is apparently based solely on the experience of the author and the Curtiss-Wright Corp., as no citations to earlier work are given. The curve that gave rise to Wright's law describes the relationship between the number of airplanes in a batch that has been contracted for, and the cost of the labor involved in manufacturing them. The author suggests the formula $F=N^x$, where N is the number of airplanes in the order, x has a fractional value (he gives 0.322 as the best fit to his data), and F is described confusingly but is basically labor cost (for example, airplanes produced per dollar paid in wages). $1/F=N^{-x}$ therefore represents labor productivity (for example, cost of labor per airplane produced).

This original formulation has morphed into what today is known as Wright's law, which differs from the original in major ways. In particular, the modern formulation (i) focuses not on F but on y as a name for $1/F$, so y represents productivity (e.g. per dollar) (Nagy et al. 2013); (ii) relates total costs, not just labor costs, to the quantity produced; and (iii) takes the quantity produced to be the total production over the history of the technology, rather than the number of instances in a batch made from the same design at the same factory.

Wright's law is, mathematically, not an exponential law because the exponent ($-w$) is a constant, not an independent variable. Instead it is a power law because the independent variable, N , is raised to a power (i.e., $-w$).

1.2 Related Work by Other Researchers

Basnet and Magee (2016b) approaches that question by looking at the sizes of the pools of scientific and engineering units of advancement and their propensity to interact and combine to produce new advances. The relationship between key design parameters and the level of performance of a technology is also investigated. Both of these considerations affect the speed of advance of a given technological domain.

Their analysis of the effect of the sizes of the pools of scientific and engineering ideas and their amenability to combining to give new ideas is complex and more work needs to be done to fully understand this process. However the qualitative claim that the sizes of these pools and their combinability affect the rate of technological advancement has inherent plausibility. It is easy to see how they could have such an effect, and not as easy to see how technological advancement might be immune from their influence.

The Basnet and Magee discussion of the effects of improvements in design parameters and technological performance of a domain is based on dimensional analyses. For example, for integrated circuits (the inspiration for Moore's Law), a key design parameter is the size of the individual components on a chip. Since the number of components that can fit in a given chip area is the square of the size of each component, and the clock speed is (or at any rate used to be) proportional to the component smallness, the number of computations per second per chip would be expected to go up as the third power (cube) of the feature smallness. Since feature size decreases over time, performance goes up rather quickly since raising to the third power is a powerful amplifier of the effect of feature size. Hence the rapidity of improvement in computing devices, as described by Moore's Law. To be sure their analysis is a simplification of the realities of chip design, but it is claimed to capture, enough to be useful, the essence of the problem.

As another example, for blast furnaces, a technology used for iron production, cost is considered proportional to the surface area of the furnace while productivity of the furnace is considered related to the volume it can contain. Since volume increases faster than surface area (volume is the cube of the height, width, or other linear dimension, while surface area is only the square), cost (which is associated with surface area), per unit of capacity (associated with its volume), for blast furnaces decreases for larger furnaces. Thus cost per unit of capacity is the performance metric for blast furnaces, and size as measured linearly (e.g. with a tape measure) is the key design parameter. Performance increases more slowly for blast furnaces than for chips in part because volume per unit of cost rises more slowly as a function of size than computations per second per chip rises as a function of decreasing feature size.

The cover article by (Denning & Lewis, 2017) of January 2017 issue of Communications of ACM is a discussion of Moore's law and other equations for curves specifically related to the computing field. An introduction to the original Moore's law is provided, pointing out that Moore's analysis was specifically about the number of electronic components on a chip. This has been increasing for decades with a fairly consistent doubling time. Moore's law is sometimes confused with other results about the overall increase in computation experienced by society. This article explains some of these related results. For example, although clock speed increases flattened out around the year 2000, multiple core chips can do multiple computing tasks in parallel, and data parallelism is another path to increased computation per chip.

As another example, Kurzweil's law of accelerating returns might be confused with Moore's law but discussed, instead, the price per performance of computing systems, which Kurzweil considers a more general measure of which Moore's law is a special case. The article also discusses Koomey's law, which describes the phenomenon whereby computations per kilowatt hour double every 1 1/2 years (the precise result, 1.57 years, may be more precise than justified by the noisy data that must be dealt with in such analyses). Koomey's result is especially relevant in an era of smartphones and other portable devices, given the much slower increases in battery capacity over time.

A discussion of Rock's law, which holds that chip fabrication facility construction costs double every four years, relates that to Moore's law and other descriptions of improvements in computation over time. As a prime example, the paper suggests that the chip market must double if a chip factory costing twice as much as one built earlier is to be worth constructing. This in turn is stated to imply that markets must

increase exponentially over time to permit continued construction of the new factories needed to keep Moore's-type laws going.

1.3 Significance

It is useful to know the rate of progress in space exploration, in part because that may be extrapolated to make tentative prediction about future progress. It is also important to note that an exponentially increasing market is a requirement for keeping Moore's law and Wright's law consistent with each other (discussed by Magee et al. 2016, citing Sahal 1979). Thus, a technology that does not show exponentially increasing production provides a test case for which one of the two laws might apply while the other doesn't, thus providing a data point on the question of which law is more generally applicable across technological domains.

2. METHODOLOGY

A first step in development of a metric for the rate of advancement in space exploration has been developed by the authors. Metrics have been devised for many other domains of technology and have been extensively described in the literature as noted above. Space exploration is an important technological endeavor for society and is experiencing a recent awakening of interest in transitioning from government funded missions to a mix that includes commercial missions to such bodies as the Moon, Mars, and asteroids. We seek to better understand the technological trajectory of the history of space exploration so that it might be extrapolated to obtain insight into its possible future, just as has been done with many other technological domains.

The steps we are pursuing in this task can be sequenced into the following stages.

1. **Gather the data.** Obtain and organize representative historical data on space

exploration. Using NASA-associated missions makes the data collection process more tractable. NASA missions were assumed to be representative of the total set of missions and in fact comprise a majority of them. Approximately 180 separate contacts with extraterrestrial bodies have been tabulated, which is a tractable quantity that helps make the project feasible.

2. **Quantify the data.** No doubt the performance of space technology is improving over time. Less clear however is the rate at which this is occurring. In order to identify this rate and understand if it follows an exponential trajectory analogous to Moore's law originally developed for electronic chip technology and found applicable to many other technological domains, or if instead it follows a power law trajectory like Wright's law, or some other path, we must first assign numbers to descriptive data records.
3. **Mine the numbers.** The numbers used to quantify the data can next be used to try to fit a curve to the historical data. This curve may reveal an exponential, power, or other historical trajectory that can be extrapolated to help see into the crystal ball of future space exploration.
4. **Analyze the historical trend: Moore's law.** Past performance of technology in the domain of space exploration will be analyzed to determine how well it fits a Moore's law-like trajectory (i.e., an exponential increase over time).
5. **Analyze the historical trend: Wright's law.** The historical performance of space exploration technology will also be checked against a Wright's law-like trajectory (i.e. an improvement in cost per unit of performance).

6. **Determine if Moore and Wright are compatible.** Sahal (1979) identified how Moore's and Wright's laws can be mathematically equivalent under certain conditions. Following his criteria we can determine if this equivalence result applies to space exploration technology. If so, both Moore's law and Wright's law apply. If not, one will fit the historical data (and, we conjecture, future performance as well) better than the other.
7. **If incompatible, choose the more accurate law.** Magee et al. (2016) compare Moore's and Wright's laws for various technologies, finding domains in which Sahal's equivalence holds and a few domains in which incompatibility applies. Those domains then provide test cases as to which law is more accurate. This is an important question for the field of technology foresight in general (ibid.). We will do this for the space technology domain.
8. **If incompatible, determine the best weighted average of the laws.** Under the assumption that both Moore's and Wright's laws model underlying processes in advancement of technological performance, both laws can be viewed as capturing important aspects of the realities of technology advancement. We plan to obtain a weighted average of the two that best matches the historical record for the domain of space exploration, and hypothesize that the weighting factor captures the relative presence of those processes of technical performance improvement that lead to Moore's law as compared to the relative presence of those processes leading to Wright's law.

3. RESULTS

We have chosen as a data set the missions referenced by NASA on their website (NASA, 2017). This gives an alphabetical list useful in generating a table of contacts by spacecraft with extraterrestrial bodies. Data for the missions were obtained from the NASA webpages and wherever else the necessary details could be gleaned for the data table, including Wikipedia (2017), a surprisingly detailed source of information about space missions due to the apparent interest in editors about making such information more available. Missions that do not result in such a contact were not analyzed further, so our investigation is limited to actual interactions with astronomical objects which were due, at least in part, to NASA funding (see the next section for how this limited objective could be expanded).

The key characteristics of the data records that we currently account for in our base data table are the mission name, extraterrestrial object, type of contact, and date of contact. The entire data table is too long to be shown here but the data acquisition stage has been completed and the first portion of the table is shown in Table 1. This illustrates the form of the data that we have acquired in step 1 above.

To analyze the data table we must quantify it by assigning a number to the technical performance represented by each row. This number must reflect the performance expressed by the row. A variety of possibilities exist for this quantification (step 2 above). Type of contact, how much the astronomical object has been contacted before, and difficulty of accessing the object in question are all valid considerations and can all be investigated as part of the mining process.

Mission Name	Astronomical Body	Date of Contact	Key Type(s) of Contact
ACE	Sun	8/25/1997	Orbit
Apollo 8	Moon	12/24/1968	Manned, Return, Orbit
Apollo 10	Moon	2/18/1969	Return, Manned, Orbit
Apollo 11	Moon	07/20/1969	Soft Landing, Manned, Return

Table 1. The first few data from the full table that we have compiled.

In our first mining operation we have chosen to focus on the type of contact. Unarguably, putting a spaceship into orbit around an object is more of an achievement than a distant flyby. Similarly, landing an astronaut is even more of an achievement, as is landing a robotic rover.

Our partial ordering of contact types is shown in Figure1.

4. CONCLUSIONS AND FUTURE DIRECTIONS

Step 1 in the research plan has been completed and step 2 is currently underway. As we complete further steps the desired goals of the project will progressively come into view.

Extensions of the research plan might perhaps suggest themselves to the reader. We could, for example, expand the data beyond NASA. Although historically NASA has been the dominant player in space exploration as the sole source of funding for many missions and in collaboration with other space agencies internationally in many more, there are also missions that have not involved NASA and thus do not appear in our table at this stage in the project. Additionally commercial missions that do not involve NASA may become more significant in the future.

Another possible extension to the project is to account for the many space missions that do not involve some form of contact with an extraterrestrial object. For example many, many missions involve orbiting the Earth. Accounting for these would provide a much finer grained

view of spacefaring activities but would present a daunting data collection task.

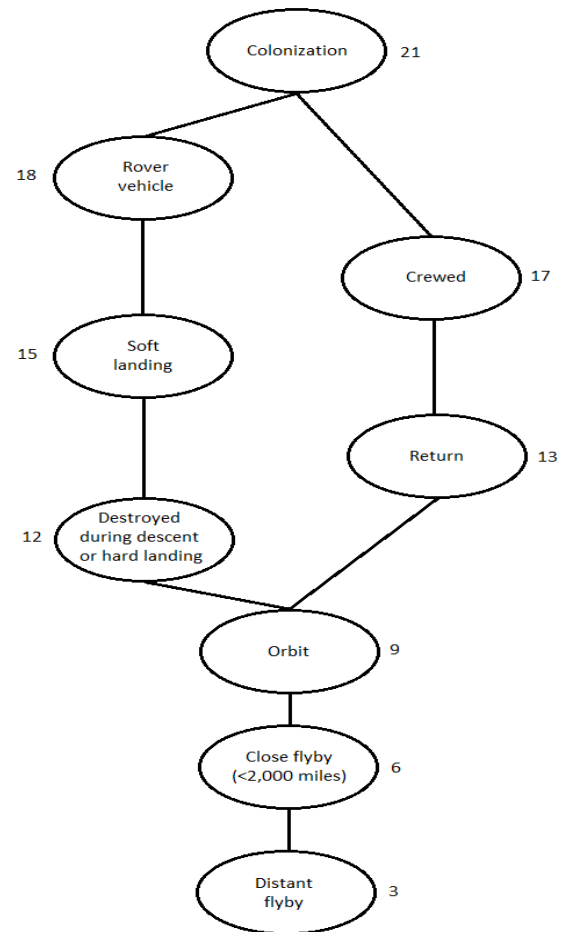


Figure 1: Each (mission, astronomical body) pair is assigned the numerical value of the highest contact type in the hierarchy that applies. For example, if a mission orbited the moon, then sent a probe that crashed to the surface, and then returned, its value would be 13 because the Return contact type is higher than the others.

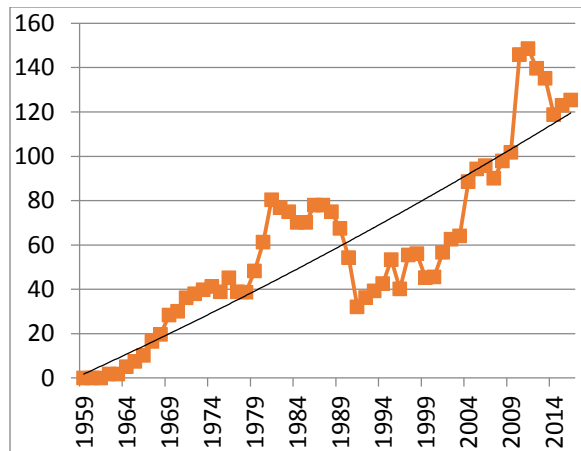


Figure 2. Technical performance for space travel (initial model) with fitted trend line. NASA missions and missions with NASA contributions are included. Each contact score (see Figure 1) is multiplied by a destination score of 0 for Earth and Sun, 1 for the Moon, 2 for Venus, 3 for Mars, 4 for Mercury, 5 for asteroids and comets, 6 for Jupiter and its moons, 7 for Saturn and its moons, 8 for Uranus and its moons, 9 for Neptune and its moons, and 10 for Pluto and its moons. The yearly totals of these scores were smoothed by 10-year lagging averaging.

Ultimately an understanding of the trajectory of technical performance in the domain of space exploration will provide informed foresight into the likely future trajectory of the field (though actual prediction of future events will always be problematic). Better foresight can in turn help inform technology policy, as well as provide society with an exciting window on the prospects of such cultural desires as eventual colonization of distant objects and further exploration of the cosmos.

5. REFERENCES

- [1] Basnet, S. & Magee, C.L. (2016a). Dependence of technological improvement on artifact interactions, arXiv preprint [arXiv:1601.02677](https://arxiv.org/abs/1601.02677), 2016, arxiv.org
- [2] Basnet, S. & Magee, C.L. (2016b). Modeling of technological performance trends using design theory, *Design Science*, v.2, e8, June 15, arXiv preprint [arXiv:1602.04713](https://arxiv.org/abs/1602.04713), 2016, arxiv.org
- [3] Denning, P. J. & Lewis, T.G. (2017). Exponential Laws of Computing Growth. *Communications of the ACM*, v.60, no.1, pp. 54-72
- [4] Magee, C.L., Basnet, S., Funk, J.L. and Benson, C.L. (2016), Quantitative empirical trends in technical performance, *Technological Forecasting and Social Change*, Elsevier, also appeared as **MIT Working Paper No. (ESD-WP-2014-22)**, Cambridge, MA, [dx.doi.org/10.1016/j.techfore.2015.12.011](https://doi.org/10.1016/j.techfore.2015.12.011)
- [5] Nagy, B., Farmer, J.D. & Bui, Q.M. & Trancik, J.E. (2013). Statistical Basis for Predicting Technological Progress, *PLOS One*, Feb, vol. 8, no. 2, e52669.
- [6] NASA (2017). NASA Missions, www.nasa.gov/missions
- [7] Sahal, D. (1979)., A theory of progress functions, *AIIE Transactions* (American Institute of Industrial Engineers), vol. 11, no. 1, pp. 23-29, 1979, [dx.doi.org/10.1080/05695557908974396](https://doi.org/10.1080/05695557908974396)
- [8] Sole, R.V., Amor, D.R., Valverde, S. (2014). On singularities in combination-driven models of technological innovation, *arXiv*: 1407.6890.
- [9] Wikipedia (2017). List of NASA Missions, en.wikipedia.org/wiki/List_of_NASA_missions
- [10] Wright, T.P. (1936). Factors Affecting the Cost of Airplanes, *Journal of the Aeronautical Sciences*, vol. 3, Feb., pp. 122-128.