UN Sustainable Development Goals: how can sustainable/green chemistry contribute? A Moore's Law for Chemistry

Martyn Poliakoff,[a] Peter Licence[a] and Michael W. George[a,b]

[a] School of Chemistry, University of Nottingham, University Park, Nottingham, NG7 2RD, UK.
[b] Department of Chemical and Environmental Engineering, University of Nottingham Ningbo China, 199 Taikang East Road, Ningbo 315100, China.

Email: martyn.poliakoff@nottingham.ac.uk, peter.licence@nottingham.ac.uk mike.george@nottingham.ac.uk

Abstract: We suggest that the future use of chemicals could be transformed if society were to adopt a Moore's Law for Chemistry (MLFC), namely that, wherever, possible, the amount of chemical(s) used to achieve a given effect should be decreased by a factor of 2 every five years.

Keywords: Sustainability; Moore's Law; F-factor; Green Chemistry.

The advent of Green Chemistry, some 25 years ago provided a fresh starting point for many chemists to carry out their work in a more environmentally friendly way. There is continuing debate as to the precise origins of Green Chemistry. Undoubtedly some, if not many, of the concepts were first applied in the late 1970s and 1980s (see references 2 and 3). However, it is also clear that Sheldon's encapsulation of the E-factor (kg of waste/kg of product)[4] and the formalization of the 12 Principles of Green Chemistry by Warner and Anastas[5] gave the field a major boost and greater coherence. These concepts have demonstrably influenced synthetic strategies and manufacturing routes in, for example, the pharmaceutical industry.[6,7]

Green Chemistry focuses particularly on the reduction of risk to human health or more, generally, the health of the environment. Long term sustainability *per* se is not a major goal, although Principle 7 of the 12 Principles of Green Chemistry does state that "*a raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable*". The Bruntland definition of sustainable development[9] as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" is clearly inspirational but gives little indication of how chemistry should be made sustainable. Horvath and coworkers' recent papers[10,] do make interesting suggestions of metrics for judging the sustainability of products and fuels derived by conversion of biomass but again they provide no easily identified goal.

The answers to the questions of what 'Sustainable Chemistry' actually is and how it differs from 'Green Chemistry' are still the subject of some debate. The human population is rising fast and per capita consumption is also rising; there are now more people and they are consuming more rapidly than ever before.[1] Of course, the level of consumption and the quality of life varies enormously across the world and the UN SDGs sets ambitious targets in an attempt to reduce this inequality. We strongly believe that sustainable chemistry can make a big contribution towards achieving these goals but it is unlikely to do so, if we remain on our present trajectory.

In practice, it is much simpler to see that our current trajectory is unsustainable than to define what is meant by ‘Sustainable Chemistry’. For example, unsustainability is perhaps more evident in our use of the less abundant elements (e.g. phosphorus or zinc or rare earth elements) than in our profligate use of fossil hydrocarbons because it is always possible to argue that the hydrocarbons could be replaced by conversion of biomass or atmospheric CO_2. Some of these elements could be replaced by other, more abundant elements but others like phosphorus, essential to the replication of living organisms, cannot. Pitts was one of the first to enunciate the concept of endangered elements,[11] see Figure 1. We are not destroying or consuming these elements in the same way that we consume oil but we are plundering a few concentrated sources of these elements and then distributing them so thinly across the planet that they are no longer recoverable at any reasonable economic cost. In effect, we are being defeated by entropy.

Sustainable Chemistry has an emphasis on industrial application and implementation. Much of the new science badged under the banner of “Green Chemistry” has yet to find application in industry. This is surprising because atom efficient processes delivering molecules of impact with lower levels of toxicity and minimal environmental harm should surely be good. However, advances in the optimisation of industrial processes have transformed existing synthetic routes making them simultaneously more profitable and less harmful to the environment along the way. It should be noted that currently the prime driver for such developments is almost invariably economic. The rising cost of waste disposal has driven process design towards the reduction of unnecessary costs and promotion of cleaner methodologies.

In principle there should be common goals for both the scientific and business communities, namely working towards satisfying the demands of an increasing global population on a sustainable basis. There is significant complexity in the supply, demand and business models for implementing sustainable chemicals manufacture. Furthermore, achieving full sustainability timescale is likely to be a lengthy process, longer than the short-term horizons of much of the chemical using industries. Industrial development over past 100 years is driven by financial considerations, products deliver a function but they also provide an income. The number of income streams have been reduced as environmental legislation squeezes down and new costs are added to clean up waste. Things are beginning to change. The wider appreciation of critical resources has led to increased interest in the circular economy[13] which has now been taken up quite widely.[14]

In this paper we suggest a different strategy for achieving sustainability. We propose that sustainable chemistry requires some overarching goal that can be embraced by everyone in the field as well as by the public in general. Our thinking is shaped by the development of the electronics industry which has been truly transformational over our lifetimes. For example, this paper is being typed on a notebook computer which is more powerful and has more memory and storage than major mainframe computer installations of a few decades ago. These developments have been encapsulated by the so-called Moore’s Law,[15] which broadly stated that the number of transistors per unit area of an integrated circuit would double every 12-18 months with a corresponding drop in unit cost of manufacture, and this has held true[16] since 1965 (see Figure 2).

Our contention is that most users of chemicals whether specialist or the public are more interested the effect that those chemicals produce rather than the amount of actual chemical that is purchased or used. Thus, they expect a medical condition to be improved by a pharmaceutical, surface tension to be reduced by a surfactant, corrosion to prevented, a reaction to be catalysed and so on. We have already suggested that chemists should start using the “F-factor”, the amount of chemical that is need to create a given effect and we illustrate its use in the context of reducing the weight of the PET bottles used for drinking water.[17] Now we propose that this approach should lead to a new concept, a Moore’s Law for chemistry (MLFC) namely that over a given period, say five years, sustainable chemists should try to reduce the amount of chemical needed to produce a given effect by a factor of two and this process should be repeated for a number of cycles. The key will be to make the economics work for everyone and this would require a change in business model for the chemicals market. This could well be consumer driven rather than imposed by the suppliers, though it might require legislation to catalyse the change. In addition, customers will have to accept that they are, in essence buying a service, rather than a quantity of chemicals. This can be thought of as building on the concept of “chemical leasing”, an approach which is gradually gaining ground.[18]

In principle, addressing the challenges of the MLFC will be different from the original Moore’s Law because that was based on ever more precise engineering while the MLFC is based on molecular properties which often differ in size by orders of magnitude. It would be achieved by a combination of new chemicals and products as well as smarter use of existing ones. The reduction might be particularly straightforward for use of solvents where increasing the concentration of reactants could reduce the usage of solvents or increase the amount of product made with a given amount of solvent. The case of Viagra manufacture is a particularly good demonstration of solvent reduction where the volume of solvent per kilo of product was reduced from 1300 to 6.5 litres.[6]

Therefore, the goals of the MLFC might be easier to achieve in some areas than in others but the ultimate reduction would not need to nearly as dramatic as for integrated circuits. Six cycles of the MLFC, namely a reduction in chemical usage by x64 (i.e. 2^6) might be sufficient to make a huge impact on the sustainability of the chemical enterprise. Even less might be required if the MLFC were to be accompanied by a parallel effort to increase the serviceable lifetime of at least some of the chemical-containing products and replacement of single-use items with those that could be used multiple times. The overall usage of chemicals could be further reduced by designing products that are easily recycled or disassembled for reuse, as well as recycling within chemical processes and making better use of unavoidable by-products.

Some customer education and considerable innovation will be required to make people accept longer lifetimes for their possessions. Much of the problem lies in changing human behaviour which is often complex as exemplified by how frequently people upgrade their smartphone. However, recent developments with vehicles has shown that change is much more possible than we expect; the unthinkable replacement of the internal combustion engine has become a likely reality in a period of only a few months, partly as a consequence of issues with diesel emissions.[20]

Chemicals are central to achieving many of the SDGs including zero hunger, health and wellbeing, clean water and clean energy. So how will the MLFC impact on the SDGs? First, and most importantly, the MLFC could reduce demand for chemicals from currently developed countries so that existing manufacturing facilities can produce a surplus to address the needs of those in economically developing regions. Secondly, the MLFC will change the way that people think about chemicals and it will give everyone a shared vision of how our use of chemicals can become sustainable.

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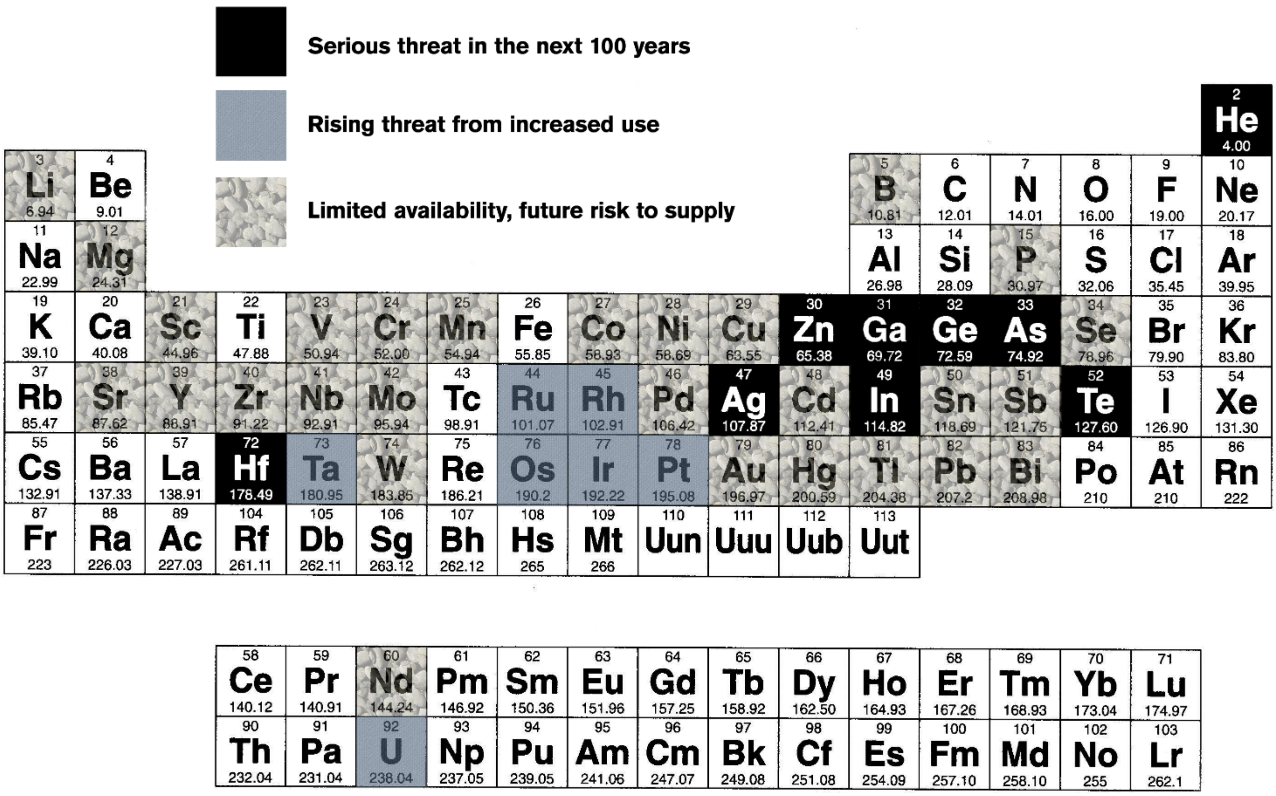

Figure 1: The Periodic Table of “Endangered Elements” ignoring radioactive elements apart from U. Adapted from Ref 12.

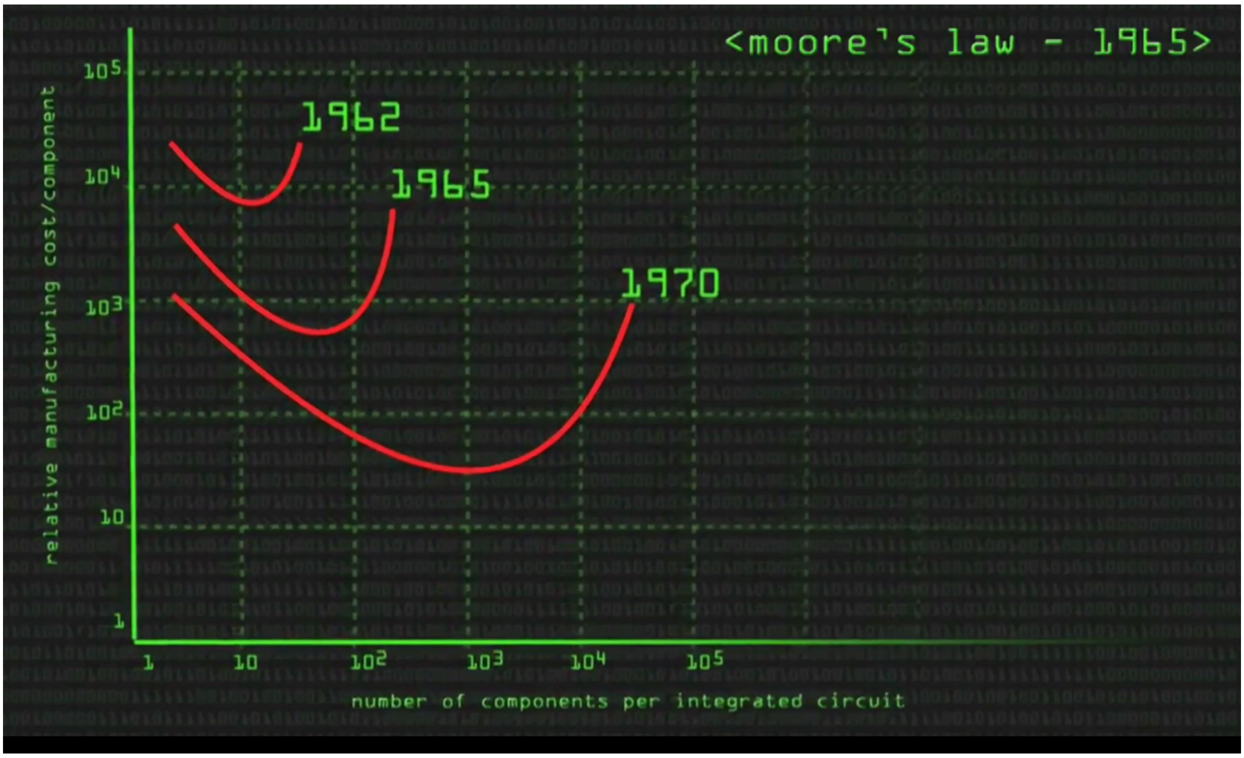

Figure 2 The early embodiment of Moore's Law. Reproduced with permission from Ref 20.