What should the UK do about semiconductors?

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The UK government is currently in the process of writing a new strategy for semiconductors. This piece sets out some of the context for this strategy.

In this first part, I discuss the new global environment, in which a tenser geopolitical situation has revived a policy climate around the world which is much more favourable to large scale government interventions in the industry. I'll sketch the global state of the semiconductor industry and try to quantify the UK's position in the semiconductor world.

In the second part, I'll discuss the past and future of semiconductors, mentioning some of the important past interventions by governments around the world that have shaped the current situation, and I'll speculate on where the industry might be going in the future.

Finally, in the third part, I'll ask where this leaves the UK, and speculate on what its semiconductor strategy might seek to achieve.

As recent events have shown, the semiconductor industry is one of the most strategically important industries in the world, so it's going to be very important for the UK government to get its strategy right. But there are more general principles at stake. We're at a moment when a worldwide consensus behind the ideas of free trade and laissez-faire economics is being rapidly replaced in the major economies of the world by much more interventionist, and assertively nationalist, industrial policies. This isn't comfortable territory for the British state, so how it responds to this test case will be very telling.

Part 1: the UK's place in the semiconductor world

1.1 War, Semiconductors and the CHIPS act

It's been reported that Russia has been dismantling washing machines to extract their integrated circuits, for use in missiles. True or not, this story illustrates two important features of the modern world. Integrated circuits – silicon chips – are now ubiquitous and indispensable for modern living – they're not just to be found in computers and mobile phones; they're in automobiles, consumer durables, even toys. And modern precision-guided weapon systems depend on them, so with a European war entering its second year, their strategic importance couldn't be more obvious.

If demand for integrated circuits and other semiconductors is ubiquitous, we've also been reminded that their supply isn't secure. The pandemic led to severe supply chain disruptions, in turn leading to major losses of production in the global automobile industry. The manufacture of the most technically advanced integrated circuits is concentrated in a single company – TSMC – located in the contested territory of Taiwan. This dependence means that, if the People's Republic of China invades Taiwan, the consequences to the world economy would be disastrous.

This is the context for the USA's CHIPS and Science Act – a hugely significant, and expensive, government intervention to rebuild the USA's manufacturing capacity in the most advanced semiconductors. Underlying this is a serious attempt to restore its own technological supremacy – and specifically, to maintain its technological superiority over China.

This is the return, at scale, of industrial strategy. The primary driving force, as it was in the 1950's and 60's, is geopolitics, but the economic and political dimensions are important too, with an emphasis on restoring manufacturing – and the good jobs it provides – to communities that have suffered from deindustrialisation. The Act provides for expenditures, over five years, of $39 billion on incentives to return more semiconductor manufacturing to the USA, $13.2 billion for additional research and development, and $10 billion to create regional innovation hubs in economically lagging parts of the country.

It's worth stressing what an ideological about-turn this represents. An economic advisor to the first President Bush reputedly said *"Potato chips, computer chips, what's the difference? A hundred dollars of one or a hundred dollars of the other is still a hundred dollars"*. This is a marvellously succinct expression of the neoliberal argument against sector-based industrial strategy. It's now clear how naive this view was. Crisps weren't about to see the most rapid period of technological progress in history, propelling those countries like Taiwan and Korea that took advantage of this opportunity, from middle income economies, into the ranks of rich countries at the technological frontier. And Frito-Lay doesn't make missiles.

The European Union has responded with its own European Chips Act. This includes an €11 billion "Chips for Europe Initiative", together with further coordination of R&D and education and skills initiatives. Most significantly, it proposes a relaxation of state aid rules, allowing member states to directly subsidise new manufacturing facilities in Europe.

How should the UK respond to this new environment? The government is preparing a Semiconductor Strategy, but this has been repeatedly delayed.

1.2 The global semiconductor industry

What are the products of the global semiconductor industry? The most high profile are enormously complex integrated circuits that power our personal computers, gaming stations and mobile phones, as well as driving the giant server farms that underly cloud computing. The most important component of modern electronics is the transistor, a solid state switch. A few transistors can be combined to make a logic gate – the basic unit of a computer; the way this is done is described as "complementary metal oxide silicon" – hence CMOS. An integrated circuit combines a number of transistors on a single piece of silicon – a chip. Different designs of integrated circuits produce central processing units (CPUs), graphical processing units (GPUs), and solid state memory.

The more transistors the chip has, the more computing power or the bigger the memory, so the history of microelectronics is a story of miniaturisation, with each generation of chips having more transistors on a single integrated circuit, as expressed by Moore's law. A modern CPU (such as Apple's M1, made by TSMC) has 16 billion transistors, each of which has dimensions measured in nanometers. These are made by the most sophisticated and precise manufacturing processes in the world, through the successive deposition of layers of different materials, at each stage etching the layers with patterns that define the components.

Only three companies in the world have the capability to operate at this technological frontier: the USA's Intel, Korea's Samsung, and Taiwan's TSMC. In recent years, progress at Intel has stumbled, and TSMC has taken a commanding lead for the manufacturing the highest performance integrated circuits. TSMC focuses purely on manufacturing, making integrated circuits to the designs of so-called fabless companies, such as Nvidia. Intel, on the other hand, designs its own chips and manufactures them.

The scale of capital investment required to make these advanced circuits is breathtaking. TSMC is reported to have invested $60 billion in its facilities to manufacture chips at the 3 nm and 5 nm nodes. TSMC has been incentivised by the US government to establish production in Arizona, at a cost of $40 bn. These huge capital sums reflect the high cost of the ultra-sophisticated, high precision equipment required to pattern these circuits on the nanoscale. The frontier processes rely on the extreme-UV lithography systems made by the Dutch company ASML, a single unit of which may cost $150 million. Other important centres of equipment production include Japan and the USA.

There is still substantial demand for less advanced integrated circuits, for applications in cars, consumer durables, industrial machinery, weapons systems and much else. In addition to the three industry leaders, companies like Global Foundries, STMicro and NXP operate manufacturing plants in the USA, Europe and Singapore. China's leading semiconductor company, Semiconductor Manufacturing International Corporation, falls into this category, though it has aspirations to reach the technological frontier, and is supported in this goal by China's government.

Not all semiconductors are silicon. Other materials – compound semiconductors, such as Gallium Arsenide, and Gallium Nitride – are particularly important for optoelectronics; the business of converting electricity to light and back again. These are the materials from which solid state lasers and light emitting diodes are made ; familiar in everyday life as scanners in supermarkets and low energy light bulbs, but no less importantly the technologies which make the internet possible, converting electronic signals into the optical pulses that transmit information at huge rates through optical fibres.

The primary driving force for innovation in semiconductors has been information and communication technology – the desire for more powerful computers and the higher rates of data transmission that make possible today's internet. But information processing isn't the only important use of semiconductors. In power electronics, the focus is on the switching, amplifying and transformation of the much higher currents needed to drive electric motors. These technologies are rapidly growing in importance; the transition to a net zero greenhouse gas energy economy is going to be driven by the replacement of internal combustion engines by electric motors. The growth of electrical vehicles, the growing importance of renewable energy and the need for energy storage, all will drive the need to efficiently handle and transform high power electricity using light and efficient solid state devices.

1.2 The UK's place in the semiconductor world

The UK is not a big player in the global semiconductor industry. Its exports of integrated circuits, worth $1.63 bn, represent 0.24% of the world's trade; insignificant compared to the world's leaders, Taiwan, China and Korea, whose exports are worth $138 bn, $120 bn, and $89.1 bn respectively. Outside the Far East, the USA exports $44.2 bn; it's this relatively weak position relative to the East Asian countries that has prompted the measures of the CHIPS Act. In Europe, the leading exporters are Germany and Ireland, at $12.8 bn, and $11.2 bn respectively.

As mentioned above, the manufacture of integrated circuits is hugely capital intensive, so it's important to look at the suppliers of the equipment used to make chips. The export trade here is dominated by Japan, the Netherlands and the USA, worth $12 bn, $11.7 bn, and $10.7 bn respectively. The UK has 1.06% of the world market, with exports worth $497m.

One other important component of the supply chain for chip manufacture are the chemicals and materials needed. These include the silicon single crystals from which the wafers are made, amongst the purest substances ever made by man, a wide range of industrial gases and solvents and reagents, all supplied at very high purity grades, and highly optimised speciality chemicals – e.g. the materials that make up the photoresists. This sector is dominated by Japan, with exports worth $4.23 bn worth, representing 29.5% of the world trade. Here the UK exports $212 m, a 1.48% share of the world market.

It's worth reflecting on these figures in the context of the UK's overall trade position. The total value of its exports in 2020 were $700 bn, made up of $371 bn in products, and $329 bn in services, so these three semiconductor-related sectors amount to about 6.3% of its total product exports. But as these figures emphasise, service sector exports are particularly important for the UK, and this bigger story is mirrored in the semiconductor sector.

The most significant semiconductor company in the UK doesn't make any semiconductors – ARM designs chips, deriving its income from royalties and licensing fees for its intellectual property. Its revenues of $2.7 bn in 2021 would have made a significant contribution to the UK's service exports (2020 UK service exports included $21.3 bn in royalties and license fees). Smaller companies, such as Imagination and Graphcore, are similarly focused on design rather than manufacturing.

In recent years, the question of ownership of ARM has achieved prominence. Originally a public company listed on the London Stock Exchange, ARM was acquired by the Japanese finance house SoftBank in 2016. A proposed sale to the US firm Nvidia collapsed last year after concerns from regulators in the UK, the USA and the EU that the acquisition would seriously reduce competion. SoftBank still remains keen to sell the company, so the future ownership and control of ARM remains in question.

Part 2: the past and future of the global semiconductor industry

2.1 Active industrial policy in the history of semiconductors

The history of the global semiconductor industry involves a dance between governments around the world and private companies. In contrast to the conviction of the predominantly libertarian ideology of Silicon Valley, the industry wouldn't have come into existence and developed in the form we now know without a series of major, and expensive, interventions by governments across the world.

But, to caricature the claims of some on the left, there is an idea that it was governments that created the consumer electronic products we all rely on, and private industry has simply collected the profits. This view doesn't recognise the massive efforts private industry has made, spending huge sums on the research and development needed to perfect manufacturing processes and bring them to market. Taking the USA alone, in 2022 US the government spent \$6 billion on semiconductor R&D, compared to private industry's \$50.2 billion.

The semiconductor industry emerged in the 1960s in the USA, and in its early days more than half of its sales were to the US government. This was an early example of what we would now call "mission driven" innovation, motivated by a "moonshot project". The "moonshot project" of the 1960s was driven by a very concrete goal – to be able to drop a half-tonne payload anywhere on the earth's surface, with a precision measured in hundreds of meters.

Semiconductors were vital to achieve this goal – the first mass-produced computers based on integrated circuits were developed as the guidance systems of Minuteman intercontinental ballistic missiles. Of course, despite its military driving force, this "moonshot" produced important spin-offs – the development of space travel to the point at which a series of manned missions to the moon were possible, and increasing civilian applications of the more much cheaper, more powerful and more reliable computers that solid-state electronics made possible.

The USA is where the semiconductor industry started, but it played a central role in three East Asian development miracles. The first to exploit this new technology was Japan. While the USA was exploiting the military possibilities of semiconductors, Japan focused on their application in consumer goods.

By the early 1980's, though, Japanese companies were producing memory chips more efficiently than the USA, while Nikon took a leading position in the photolithography equipment used to make integrated circuits. In part the Japanese competitive advantage was driven by their companies' manufacturing prowess and their attentiveness to customer needs, but the US industry complained, not entirely without justification, that their success was built on the theft of intellectual property, access to unfairly cheap capital, the protection of home markets by trade barriers, and government funded research consortia bringing together leading companies. These are recurring ingredients of industrial policy as executed by East Asian developmental states, first executed successfully in Taiwan and in Korea, and now being applied on a continental scale by China.

An increasingly paranoid USA's response to this threat from Japan to its technological supremacy in semiconductors was to adopt some industrial strategy measures itself. The USA relaxed its stringent anti-trust laws to allow US companies to collaborate in R&D through a consortium called SEMATECH, half funded by the federal government. Sematech was founded in 1987, and in the first 5 years of its operation was supported by $500 m of Federal funding, leading to some new self-confidence for the US semiconductor industry.

Meanwhile both Korea and Taiwan had identified electronics as a key sector through which to pursue their export-focused development strategies. For Taiwan, a crucial institution was the Industrial Technology Research Institute, in Hsinchu. Since its foundation in 1973, ITRI had been instrumental in supporting Taiwan's industrial base in moving closer to the technology frontier.

In 1985 the US-based semiconductor executive Morris Chang was persuaded to lead ITRI, using this position to create a national semiconductor industry, in the process spinning out the Taiwan Semiconductor Manufacturing Company. TSMC was founded as a pure-play foundry, contract manufacturing integrated circuits designed by others and focusing on optimising manufacturing processes. This approach has been enormously successful, and has led TSMC to its globally leading position.

Over the last decade, China has been aggressively promoting its own semiconductor industry. The 2015 "Made in China 2025" identified semiconductors as a key sector for the development of a high tech manufacturing sector, setting the target of 70% self-sufficiency by 2025, and a dominant position in global markets by 2045.

Cheap capital for developing semiconductor manufacturing was provided through the state-backed National Integrated Circuit Industry Investment Fund, amounting to some $47 bn (though it seems the record of this fund has been marred by corruption allegations). The 2020 directive "Several Policies for Promoting the High-quality Development of the Integrated Circuit Industry and Software Industry in the New Era" reinforced these goals with a package of measures including tax breaks, soft loans, R&D and skills policies.

While the development of the semiconductor industry in Taiwan and Korea was generally welcomed by policy-makers in the West, a changing geopolitical climate has led to much more anxiety about China's aspirations. The USA has responded by an aggressive programme of bans on the exports of semiconductor manufacturing tools, such as high end lithography equipment, to China, and has persuaded its allies in Japan and the Netherlands to follow suit.

Industrial policy in support of the semiconductor industry hasn't been restricted to East Asia. In Europe a key element of support has been the development of research institutes bringing together consortia of industries and academia; perhaps the most notable of these is IMEC in Belgium, while the cluster of companies that formed around the electronics company Phillips in Eindhoven now includes the dominant player in equipment for extreme UV lithography, AMSL.

In Ireland, policies in support of inward investment, including both direct and indirect financial inducements, and the development of institutions to support skills innovation, persuaded Intel to base their European operations in Ireland. This has resulted in this small, formerly rural, nation becoming the second largest exporter of integrated circuits in Europe.

In the UK, government support for the semiconductor industry has gone through three stages. In the postwar period, the electronics industry was a central part of the UK's Cold War "Warfare State", with government institutions like the Royal Signals and Radar Establishment at Malvern carrying out significant early research in compound semiconductors and optoelectronics.

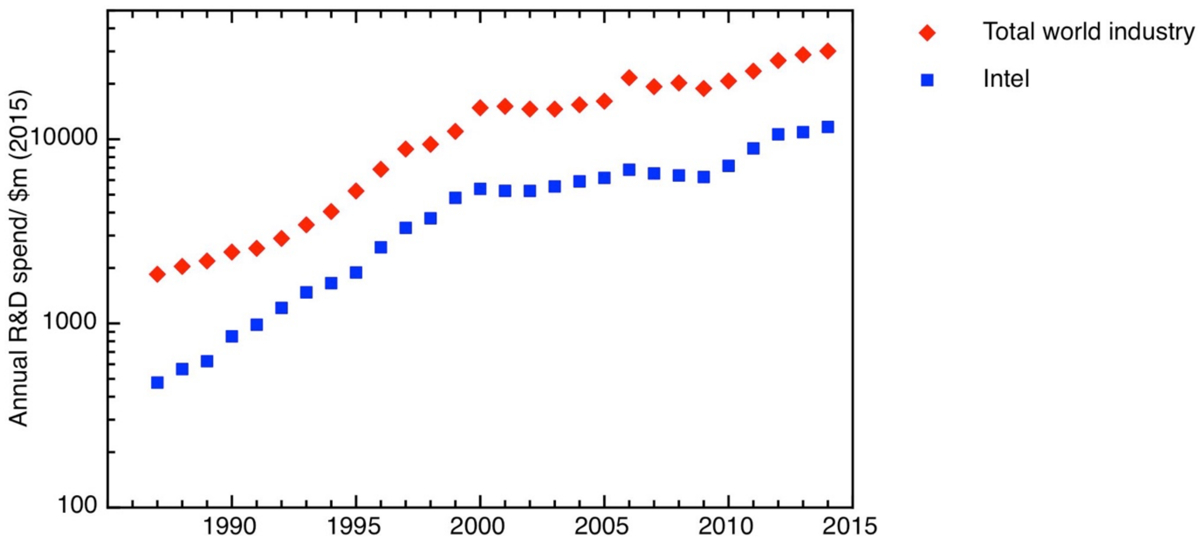
The second stage saw a more conscious effort to support the industry. In the mid-to-late 1970's, a realisation of the potential importance of integrated circuits coincided with a more interventionist Labour government. The government, through the National Enterprise Board, took a stake in a start-up making integrated circuits in South Wales, Inmos. The 1979 Conservative government was much less interventionist than its predecessor, but two important interventions were made in the early 1980's.

The first was the Alvey Programme, a joint government/private sector research programme launched in 1983. This was an ambitious programme of joint industry/government research, worth £350m, covering a number of areas in information and communication technology. The results of this programme were mixed; it played a significant role in the development of mobile telephony, and laid some important foundations for the development of AI and machine learning. In semiconductors, however, the companies it supported, such as GEC and Plessey, were unable to develop a lasting competitive position in semiconductor manufacturing and no longer survive.

The second intervention arose from a public education campaign ran by the BBC; a small Cambridge based microcomputer company, Acorn, won the contract to supply BBC-branded personal computers in support of this programme. The large market created in this way later gave Acorn the headroom to move into the workstation market with reduced instruction set computing architectures, from which was spun-out the microprocessor design house ARM.

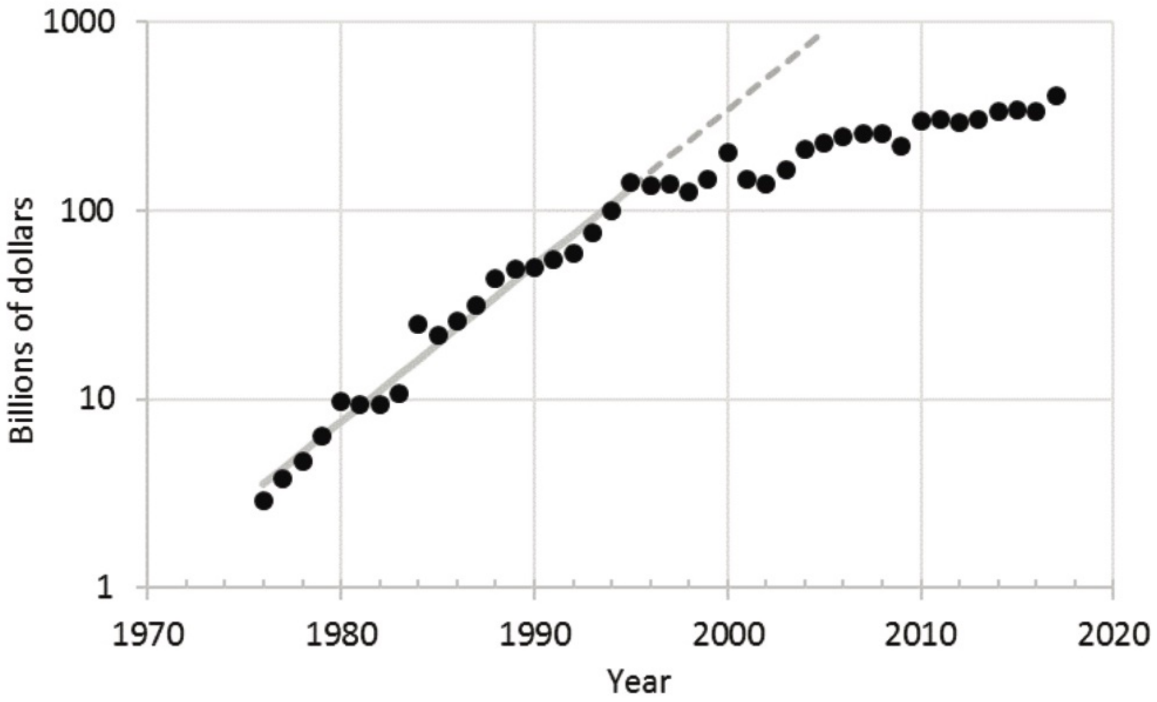
In the third stage, the UK government adopted a market fundamentalist position. This involved a withdrawal from government support for applied research and the run-down of government laboratories like RSRE, and a position of studied indifference about the acquisition of UK technology firms by overseas rivals. Major UK electronics companies, such as GEC and Plessey, collapsed following some ill-judged corporate misadventures. Inmos was sold, first to Thorn, then to the Franco- Italian group, SGS Thomson. Inmos left a positive legacy, with many who had worked there going on to participate in a Bristol based cluster of semiconductor design houses. The Inmos manufacturing site survives as Newport Wafer Fab, currently owned by the Dutch-based, Chinese owned company Nexperia, though its future is uncertain following a UK government ruling that Nexperia should divest its shareholding on national security grounds.

This focus on the role of interventions by governments across the world at crucial moments in the development of the industry shouldn't overshadow the huge investments in R&D made by private companies around the world. A sense of the scale of these investments is given by the figure below.



R&D expenditure in the microelectronics industry, showing Intel's R&D expenditure, and a broader estimate of world microelectronics R&D including semiconductor companies and equipment manufacturers. Data from the "Are Ideas Getting Harder to Find?" dataset on Chad Jones's website. Inflation corrected using the US GDP deflator.

The exponential increase in R&D spending up to 2000 was driven by a similarly exponential increase in worldwide semiconductor sales. In this period, there was a remarkable virtuous circle of increasing sales, leading to increasing R&D, leading in turn to very rapid technological developments, driving further sales growth. In the last two decades, however, growth in both sales and in R&D spending has slowed down



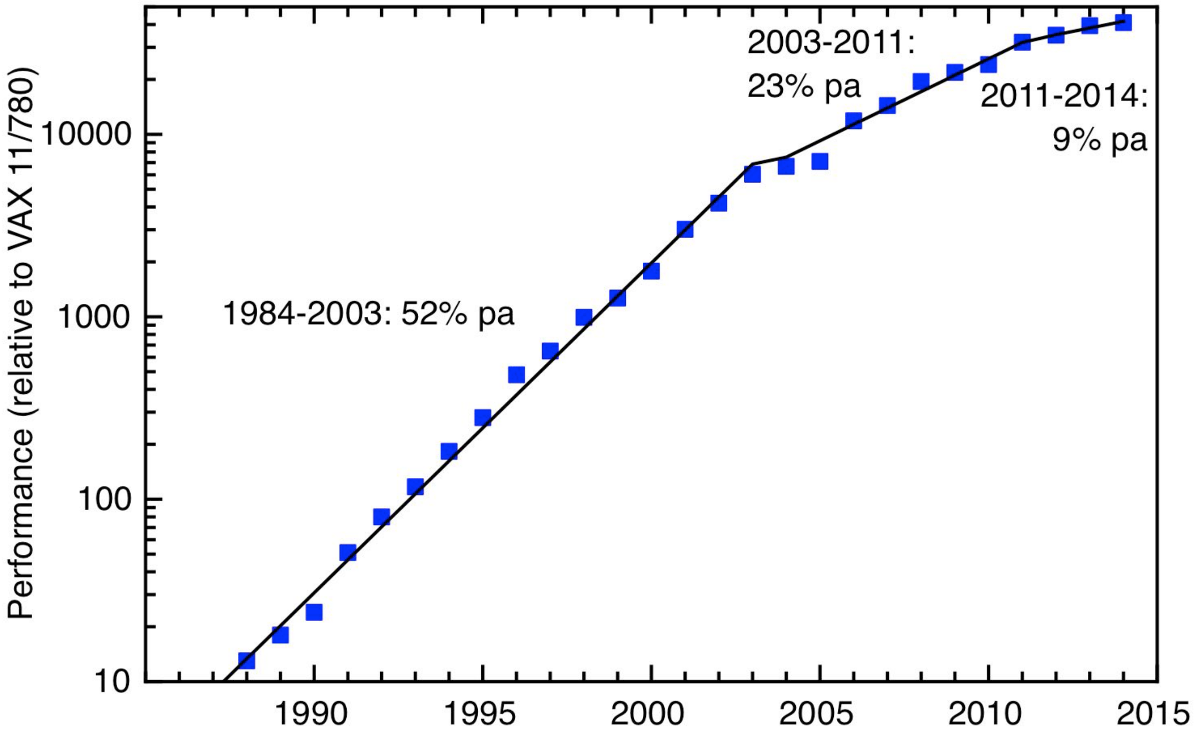
Global semiconductor sales in billions of dollars. Plot from "Quantum Computing: Progress and Prospects" (2019), National Academies Press, which uses data from the Semiconductor Industry Association.

2.2. Possible futures for the semiconductor industry

The rate of technological progress in integrated circuits between 1984 and 2003 was remarkable and unprecedented in the history of technology. This drove an exponential increase in microprocessor computing power, which grew by more than 50% a year. This growth arose from two factors, As is well-known, the number of transistors on a silicon chip grew exponentially, as predicted by Moore's Law. This was driven by many unsung, but individually remarkable, technological innovations in lithography (to name just a couple of examples, phase shift lithography, and chemically amplified resists), allowing smaller and smaller features to be manufactured.

The second factor is less well known – by a phenomenon known as Dennard scaling, as transistors get smaller they operate faster. Dennard scaling reached its limit around 2004, as the heat generated by microprocessors became a limiting factor. After 2004, microprocessor computer power increased at a slower rate, driven by increasing the number of cores and parallelising operations, resulting in rates of increase around 23% a year. This approach itself ran into diminishing returns after 2011.

Currently we are seeing continued reductions in feature sizes, together with new transistor designs, such as finFETs, which in effect allow more transistors to be fitted into a given area by building them side-on. But further increases in computer power are increasingly being driven by optimising processor architectures for specific tasks, for example graphical processing units and specialised chips for AI, and by simply multiplying the number of microprocessors in the server farms that underlie cloud computing.



Slowing growth in computer power. The growth in processor performance since 1988. Data from figure 1.1 in Computer Architecture: A Quantitative Approach (6th edn) by Hennessy & Patterson.

It's remarkable that, despite the massive increase in microprocessor performance since the 1970's, and major innovations in manufacturing technology, the underlying mode of operation of microprocessors remains the same. This is known by the shorthand of CMOS, for Complementary Metal Oxide Semiconductor. Logic gates are constructed from complementary pairs of field effect transistors consisting of a channel in heavily doped silicon, whose conductance is modulated by the application of an electric field across an insulating oxide layer from a metal gate electrode.

CMOS isn't the only way of making a logic gate, and it's not obvious that it is the best one. One severe limitation on our computing is its energy consumption. This matters at a micro level; the heat generated by a laptop or mobile phone is very obvious, and it was problems of heat dissipation that underlay the slowdown in the growth in microprocessor power around 2004. It's also significant at a global level, where the energy used by cloud computing is becoming a significant share of total electricity consumption.

There is a physical lower limit to the energy that computing uses – this is the Landauer limit on the energy cost of a single logical operation, a consequence of the second law of thermodynamics. Our current technology consumes more than three orders of magnitude more energy than is theoretically possible, so there is room for improvement. Somewhere in the universe of technologies that don't exist, but are physically possible, lies a superior computing technology to CMOS.

Many alternative forms of computing have been tried out in the laboratory. Some involve different materials to silicon: compound semiconductors or new forms of carbon like nanotubes and graphene. In some, the physical embodiment of information is, not electric charge, but spin. The idea of using individual molecules as circuit elements – molecular electronics – has a long and somewhat chequered history. None of these approaches has yet made a significant commercial impact; incumbent technologies are always hard to displace. CMOS and its related technologies amount to a deep nanotechnology implemented at a massive scale; the huge investment in this technology has in effect locked us into a particular technology path.

There are alternative, non-semiconductor based, computing paths that are worth mentioning, because they may become important in the future. One is to copy biology; our own brains deliver enormous computing power at remarkably low energy cost, with an architecture that is very different from the von Neumann architecture that human-built computers follow, and a basic unit that is molecular. Various radical approaches to computing take some inspiration from biology, whether that is the new architectures for CMOS that underlie neuromorphic computing, or entirely molecular approaches based on DNA.

Quantum computing, on the other hand, offers the potential for another exponential leap forward in computing power – in principle. Many practical barriers remain before this potential can be turned into practise, however, and this is a topic for another discussion. Suffice it to say that, on a timescale of a decade or so, quantum computers will not replace conventional computers for anything more than some niche applications, and in any case they are likely to be deployed in tandem with conventional high performance computers, as accelerators for specific tasks, rather than as general purpose computers.

Finally, I should return to the point that semiconductors aren't just valuable for computing; the field of power electronics is likely to become more and more important as we move to a net zero energy system. We will need a much more distributed and flexible energy grid to accommodate decentralised renewable sources of electricity, and this needs solid-state power electronics capable of handling very high voltages and currents – think of replacing house-size substations by suitcase-size solid-state transformer. Widespread uptake of electric vehicles and the need for widely available rapid charging infrastructures will place further demands on power electronics. Silicon is not suitable for these applications, which require wide-band gap semiconductors such as diamond, silicon carbide and other compound semiconductors.

Part 3: towards a UK semiconductor strategy

To summarise the global context, the essential nations in advanced semiconductor manufacturing are Taiwan, Korea and the USA for making the chips themselves. In addition, Japan and the Netherlands are vital for crucial elements of the supply chain, particularly the equipment needed to make chips. China has been devoting significant resource to develop its own semiconductor industry – as a result, it is strong in all but the most advanced technologies for chip manufacture, but is vulnerable to being cut off from crucial elements of the supply chain.

The technology of chip manufacture is approaching maturity; the very rapid rates of increase in computing power we saw in the 1980s and 1990s, associated with a combination of Moore's law and Dennard scaling, have significantly slowed. At the technology frontier we are seeing diminishing returns from the ever larger investments in capital and R&D that are needed to maintain advances. Further improvements in computer performance are likely to put more premium on custom designs for chips optimised for specific applications.

The UK's position in semiconductor manufacturing is marginal in a global perspective, and not a relative strength in the context of the overall UK economy. There is actually a slightly stronger position in the wider supply chain than in chip manufacture itself, but the most significant strength is not in manufacture, but design, with ARM having a globally significant position and newcomers like Graphcore showing promise.

The history of the global semiconductor industry is a history of major government interventions coupled with very large private sector R&D spending, the latter driven by dramatically increasing sales. The UK essentially opted out of the race in the 1980's, since when Korea and Taiwan have established globally leading positions, and China has become a fast expanding new entrant to the industry.

The more difficult geopolitical environment has led to a return of industrial strategy on a huge scale, led by the USA's CHIPS Act, which appropriates more than $50 billion over 5 years to reestablish its global leadership, including $39 billion on direct subsidies for manufacturing.

How should the UK respond? What I'm talking about here is the core business of manufacturing semiconductor devices and the surrounding supply chain, rather than information and communication technology more widely. First, though, let's be clear about what the goals of a UK semiconductor strategy could be.

3.1 What is a semiconductor strategy for?

A national strategy for semiconductors could have multiple goals. The UK Science and Technology Framework identifies semiconductors as one of five critical technologies, judged against criteria including their foundational character, market potential, as well as their importance for other national priorities, including national security.
It might be helpful to distinguish two slightly different goals for the semiconductor strategy. The first is the question of security, in the broadest sense, prompted by the supply problems that emerged in the pandemic, and heightened by the growing realisation of the importance and vulnerability of Taiwan in the global semiconductor industry. Here the questions to ask are, what industries are at risk from further disruptions? What are the national security issues that would arise from interruptions in supply?

The government's latest refresh of its integrated foreign and defence strategy promises to *"ensure the UK has a clear route to assured access for each [critical technology], a strong voice in influencing their development and use internationally, a managed approach to supply chain risks, and a plan to protect our advantage as we build it."* It reasserts as a model introduced in the previous Integrated Review the *"own, collaborate, access"* framework.

This framework is a welcome recognition of the the fact that the UK is a medium size country which can't do everything, and in order to have access to the technology it needs, it must in some cases collaborate with friendly nations, and in others access technology through open global markets. But it's worth asking what exactly is meant by *"own"*. This is defined in the Integrated Review thus: *"Own: where the UK has leadership and ownership of new developments, from discovery to large-scale manufacture and commercialisation."*

In what sense does the nation ever own a technology? There are still a few cases where wholly state owned organisations retain both a practical and legal monopoly on a particular technology – nuclear weapons remain the most obvious example. But technologies are largely controlled by private sector companies with a complex, and often global ownership structure. We might think that the technologies of semiconductor integrated circuit design that ARM developed are British, because the company is based in Cambridge. But it's owned by a Japanese investment bank, who have a great deal of latitude in what they do with it.

Perhaps it is more helpful to talk about control than ownership. The UK state retains a certain amount of control of technologies owned by companies with a substantial UK presence – it has been able in effect to block the purchase of the Newport Wafer Fab by the Chinese owned company Nexperia. But this new assertiveness is a very recent phenomenon; until very recently UK governments have been entirely relaxed about the acquisition of technology companies by overseas companies. Indeed, in 2016 ARM's acquisition by Softbank was welcomed by the then PM, Theresa May, as being in the UK's national interest, and a vote of confidence in post-Brexit Britain. The government has taken new powers to block acquisitions of companies through the National Security and Investment Act 2021, but this can only be done on grounds of national security.

The second goal of a semiconductor strategy is as part of an effort to overcome the UK's persistent stagnation of economic productivity, to *"generate innovation-led economic growth"* , in the words of a recent Government response to a BEIS Select Committee report. As I have written about at length, the UK's productivity problem is serious and persistent, so there's certainly a need to identify and support high value sectors with the potential for growth. There is a regional dimension here, recognised in the government's aspiration for the strategy to create *"high paying jobs throughout the UK"*. So it would be entirely appropriate for a strategy to support the existing cluster in the Southwest around Bristol and into South Wales, as well as to create new clusters where there are strengths in related industry sectors

The economies of Taiwan and Korea have been transformed by their very effective deployment of an active industrial strategy to take advantage of an industry at a time of rapid technological progress and expanding markets. There are two questions for the UK now. Has the UK state (and the wider economic consensus in the country) overcome its ideological aversion to active industrial strategy on the East Asian model to intervene at the necessary scale? And, would such an intervention be timely, given where semiconductors are in the technology cycle? Or, to put it more provocatively, has the UK left it too late to capture a significant share of a technology that is approaching maturity?

3.2 What, realistically, can the UK do about semiconductors?

What interventions are possible for the UK government in devising a semiconductor strategy that addresses these two goals – of increasing the UK's economic and military security by reducing its vulnerability to shocks in the global semiconductor supply chain, and of improving the UK's economic performance by driving innovation-led economic growth? There is a menu of options, and what the government chooses will depend on its appetite for spending money, its willingness to take assets onto its balance sheet, and how much it is prepared to intervene in the market.
Could the UK establish the manufacturing of leading edge silicon chips? This seems implausible. This is the most sophisticated manufacturing process in the world, enormously capital intensive and drawing on a huge amount of proprietary and tacit knowledge. The only way it could happen is if one of the three companies currently at or close to the technology frontier – Samsung, Intel or TSMC – could be enticed to establish a manufacturing plant in the UK. What would be in it for them? The UK doesn't have a big market, it has a labour market that is high cost, yet lacking in the necessary skills, so its only chance would be to advance large direct subsidies.

In any case, the attention of these companies is elsewhere. TSMC is building a new plant in Arizona, at a cost of $40 billion, while Samsung's new plant in Texas is costing $25 billion, with the US government using some of the CHIPS act money to subsidise these investments. Despite Intel's well-reported difficulties, it is planning significant investment in Europe, supported by inducements from EU and its member states under the EU Chips act. Intel has committed €12 billion to expanding its operations in Ireland and €17 billion for a new fab in the existing semiconductor cluster in Saxony, Germany.

From the point of view of security of supply, it's not just chips from the leading edge that are important; for many applications, in automobiles, defence and industrial machinery, legacy chips produced by processes that are no longer at the leading edge are sufficient. In principle establishing manufacturing facilities for such legacy chips would be less challenging than attempting to establish manufacturing at the leading edge. However, here, the economics of establishing new manufacturing facilities is very difficult. The cost of producing chips is dominated by the need to amortise the very large capital cost of setting up a fab, but a new plant would be in competition with long-established plants whose capital cost is already fully depreciated. These legacy chips are a commodity product.

So in practise, our security of supply can only be assured by reliance on friendly countries. It would have been helpful if the UK had been able to participate in the development of a European strategy to secure semiconductor supply chains, as Hermann Hauser has argued for. But what does the UK have to contribute, in the creation of more resilient supply chains more localised in networks of reliably friendly countries?

The UK's key asset is its position in chip design, with ARM as the anchor firm. But, as a firm based on intellectual property rather than the big capital investments of fabs and factories, ARM is potentially footloose, and as we've seen, it isn't British by ownership. Rather it is owned and controlled by a Japanese conglomerate, which needs to sell it to raise money, and will seek to achieve the highest return from such a sale. After the proposed sale to Nvidia was blocked, the likely outcome now is a floatation on the US stock market, where the typical valuations of tech companies are higher than they are in the UK.

The UK state could seek to maintain control over ARM by the device of a *"Golden Share"*, as it currently does with Rolls-Royce and BAE Systems. I'm not sure what the mechanism for this would be – I would imagine that the only surefire way of doing this would be for the UK government to buy ARM outright from Softbank in an agreed sale, and then subsequently float it itself with the golden share in place. I don't suppose this would be cheap – the agreed price for the thwarted Nvidia take over was $66 billion. The UK government would then attempt to recoup as much of the purchase price as possible through a subsequent floatation, but the presence of the golden share would presumably reduce the market value of the remaining shares. Still, the UK government did spend £46 billion nationalising a bank.

What other levers does the UK have to consolidate its position in chip design? Intelligent use of government purchasing power is often cited as an ingredient of a successful industrial policy, and here there is an opportunity. The government made the welcome announcement in the Spring Budget that it would commit £900 m to build an exascale computer to create a sovereign capability in artificial intelligence. The procurement process for this facility should be designed to drive innovation in the design, by UK companies, of specialised processing units for AI with lower energy consumption.

A strong public R&D base is a necessary – but not sufficient – condition for an effective industrial strategy in any R&D intensive industry. As a matter of policy, the UK ran down its public sector research effort in mainstream silicon microelectronics, in response to the UK's overall weak position in the industry. The Engineering and Physical Research Council announces on its website that: *"In 2011, EPSRC decided not to support research aimed at miniaturisation of CMOS devices through gate-length reduction, as large non-UK industrial investment in this field meant such research would have been unlikely to have had significant national impact."* I don't think this was – or is – an unreasonable policy given the realities of the UK's global position. The UK maintains academic research strength in areas such III-V semiconductors for optoelectronics, 2-d materials such as graphene, and organic semiconductors, to give a few examples.

Given the sophistication of state of the art microelectronic manufacturing technology, for R&D to be relevant and translatable into commercial products it is important that open access facilities are available to allow the prototyping of research devices, and with pilot scale equipment to demonstrate manufacturability and facilitate scale-up. The UK doesn't have research centres on the scale of Belgium's IMEC, or Taiwan's ITRI, and the issue is whether, given the shallowness of the UK's industry base, there would be a customer base for such a facility. There are a number of university facilities focused on supporting academic researchers in various specialisms – at Glasgow, Manchester, Sheffield and Cambridge, to give some examples. Two centres are associated with the Catapult Network – The National Printable Electronics Centre in Sedgefield, and the Compound Semiconductor Catapult in South Wales.

This existing infrastructure is certainly insufficient to support an ambition to expand the UK's semiconductor sector. But a decision to enhance this research infrastructure will need a careful and realistic evaluation of what niches the UK could realistically hope to build some presence in, building on areas of existing UK strength, and understanding the scale of investment elsewhere in the world.

To summarise, the UK must recognise that, in semiconductors, it is currently in a relatively weak position. For security of supply, the focus must be on staying close to like-minded countries like our European neighbours. For the UK to develop its own semiconductor industry further, the emphasis must be on finding and developing particular niches where the UK's does have some existing strength to build on, and there is the prospect of rapidly growing markets. And the UK should look after its one genuine area of strength, in chip design.

3.3. Four lessons for industrial strategy

What should the UK do about semiconductors? Another tempting, but unhelpful, answer is *"I wouldn't start from here"*. The UK's current position reflects past choices, so to conclude, perhaps it's worth drawing some more general lessons about industrial strategy from the history of semiconductors in the UK, and globally.

1. Basic research is not enough

The historian David Edgerton has observed that it is a long-running habit of the UK state to use research policy as a substitute for industrial strategy. Basic research is relatively cheap, compared to the expensive and time-consuming process of developing and implementing new products and processes. In the 1980's, it became conventional wisdom that governments should not get involved in applied research and development, which should be left to private industry, and, as I recently discussed at length, this has profoundly shaped the UK's research and development landscape. But excellence in basic research has not produced a competitive semiconductor industry.

The last significant act of government support for the semiconductor industry in the UK was the Alvey programme of the 1980s. The programme was not without some technical successes, but it clearly failed in its strategic goal of keeping the UK semiconductor industry globally competitive. As the official evaluation of the programme concluded in 1991: *"Support for pre-competitive R&D is a necessary but insufficient means for enhancing the competitive performance of the IT industry. The programme was not funded or equipped to deal with the different phases of the innovation process capable of being addressed by government technology policies. If enhanced competitiveness is the goal, either the funding or scope of action should be commensurate, or expectations should be lowered accordingly".*

But the right R&D institutions can be useful; the experience of both Japan and the USA shows the value of industry consortia – but this only works if there is already a strong, R&D intensive industry base. The creation of TSMC shows that it is possible to create a global giant from scratch, and this emphasises the role of translational research centres, like Taiwan's ITRI and Belgium's IMEC. But to be effective in creating new businesses, such centres need to have a focus on process improvement and manufacturing, as well as discovery science.

2. Big is beautiful in deep tech.

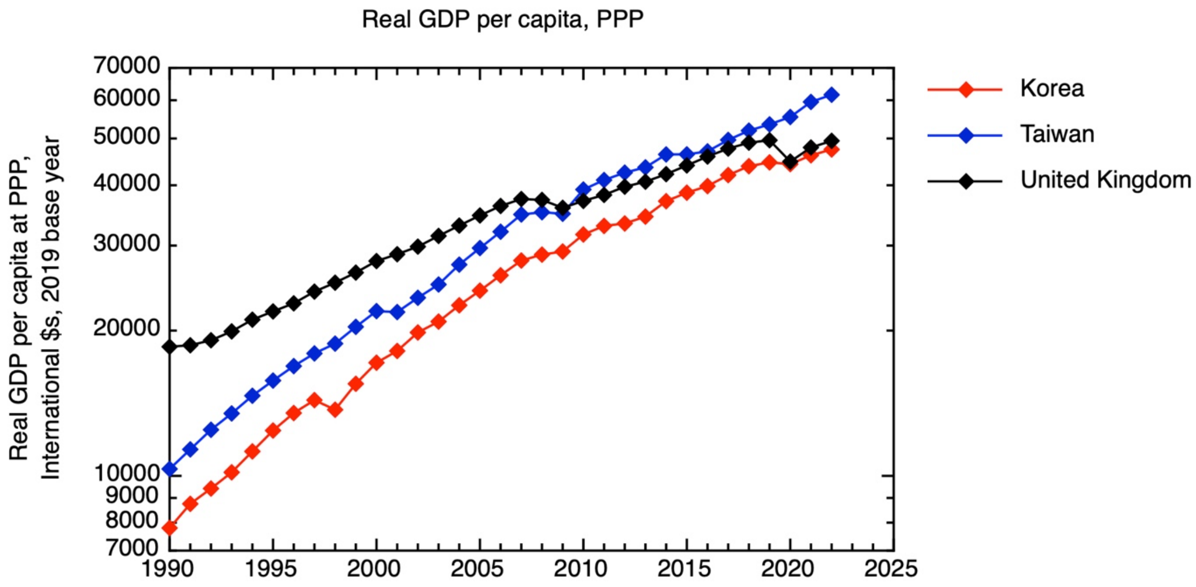
The modern semiconductor industry is the epitome of *"Deep Tech"*: hard innovation, usually in the material or biological domains, demanding long term R&D efforts and large capital investments. For all the romance of garage-based start-ups, in a business that demands up-front capital investments in the $10's of billions and annual research budgets on the scale of medium size nation states, one needs serious, large scale organisations to succeed.

The ownership and control of these organisations does matter. From a national point of view, it is important to have large firms anchored to the territory, whether by ownership or by significant capital investment that would be hard to undo, so ensuring the permanence of such firms is the legitimate business of government. Naturally, big firms often start as fast growing small ones, and the UK should make more effort to hang on to companies as they scale up.

3. Getting the timing right in the technology cycle

Technological progress is uneven – at any given time, one industry may be undergoing very dramatic technological change, while other sectors are relatively stagnant. There may be a moment when the state of technology promises a period of rapid development, and there is a matching market with the potential for fast growth. Firms that have the capacity to invest and exploit such "windows of opportunity", to use David Sainsbury's phrase, will be able to generate and capture a high and rising level of added value.

The timing of interventions to support such firms is crucial, and undoubtedly not easy, but history shows us that nations that are able to offer significant levels of strategic support at the right stage can see a material impact on their economic performance. The recent rapid economic growth of Korea and Taiwan is a case in point. These countries have gone beyond catch-up economic growth, to equal or surpass the UK, reflecting their reaching the technological frontier in high value sectors such as semiconductors. Of course, in these countries, there has been a much closer entanglement between the state and firms than UK policy makers are comfortable with.



Real GDP per capita at purchasing power parity for Taiwan, Korea and the UK. Based on data from the IMF. GDP at PPP in international dollars was taken for the base year of 2019, and a time series constructed using IMF real GDP growth data, & then expressed per capita.

4. If you don't choose sectors, sectors will choose you

In the UK, so-called *"vertical"* industrial strategy, where explicit choices are made to support specific sectors, have long been out of favour. Making choices between sectors is difficult, and being perceived to have made the wrong choices damages the reputation of individuals and institutions. But even in the absence of an explicitly articulated vertical industrial strategy, policy choices will have the effect of favouring one sector over another.

In the 1990s and 2000s, UK chose oil and gas and financial services over semiconductors, or indeed advanced manufacturing more generally. Our current economic situation reflects, in part, that choice.

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