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The emergence of nanoscience

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Abstract. Nanoscience and nanotechnology have emerged as distinct scientific concepts in the final third of the 20th century, however the way that the history of this field is discussed has not settled into an accepted path. This paper discusses the many ways to approach this history, spanning science intuition, ancient technologies, mythical visions, tool development, commercial opportunities and science fictions. In the brief and accessible discussion here expanding on the different histories of nano, the paper explores some of these concepts and conclude that this is not (yet) a well posed question.

1. Introduction

The word ‘nanotechnology’ was first used in a paper in 1974 about constructing things on the scale of a nanometre. Before then the technologies did not exist to reach this scale, but this brief historical review will tell a much richer history.

Part of the terminology in this paper comes from one of our (JJB) 2016 book “*The Secret Life of Science*”, which tries to think about how science really works in practice, a general topic which is very pertinent to nanoscience. A series of stories will be told here that break down into different ideas and then the relationships between these stories will be looked at. The first story shows how science is driven by serendipity, the second focusses on utility and the last two are about what has been called ‘simplifier’ and ‘constructor’ science.

The public perception of science is often about the process of discovering how an atom is built – what is inside a proton for example. To study this big challenge, scientists take things apart by smashing them in a particle accelerator. Other examples of scientific challenges at the moment include the origin of consciousness or how a cell works – both of these could be classified as a sort of ‘simplifier science’. In ‘constructor science’ by contrast, scientists take things that are already known but put them together in a very different way. For instance, atoms can be combined into molecules or chunks of matter can be put into structures in different ways, which results in the emergence of new properties that were not obvious from the constituents alone. In fact far more scientists in the world are constructors than simplifiers, although what mostly gets reported is simplifier science.

2. Natural nanoparticles

Firstly, a general understanding of what is meant by ‘nano’ is assumed. A nanometre is a billionth of a metre – about three gold atoms across. A thousand times bigger than that is still only a hundredth of the width of a human hair and about the minimum that can be seen in an optical microscope.

Often the public are exposed to potentially worrisome ideas such as ‘grey goo’, that nanotechnology is going to come and take over the world. But of course it must be remembered that we are surrounded by nanoparticles both inside and outside us. Proteins, which can be imaged in exquisite detail, are different sorts of nanostructures (figure 1(a)). These are nanostructures on the order of 100 nanometres across - machines that have carefully placed positive and negative charge in different places, and soft hinges.

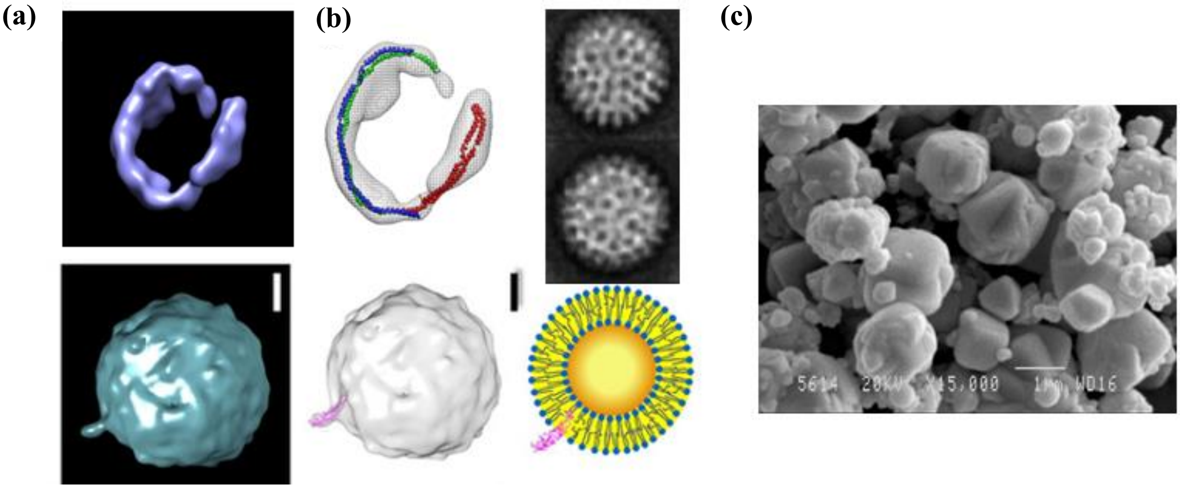

Figure 1. Natural nanostructures. **(a)** Proteins, **(b)** viruses, and **(c)** aluminosilicates.

The closer one looks, the more they seem like precisely built nanomachines. Although it is known that nature can make these on demand in vast quantity, scientists can so far replicate nothing like these proteins as will be shown later. Reproducing nature's machinery is the vision of what scientists will be doing for a good while yet, because they are still terrible at it.

Inorganic things like sand and volcanic minerals also become ground down to the nanometre scale (figure 1(b)) and we breathe them in all the time. They enter and leave our bodies and go through the pores in our skin, but the body is very good at dealing with things on that scale.

Then there are beautiful structures like viruses. The virus in figure 1(c) is constructed of thirty eight different units that tessellate perfectly together to produce a symmetrical structure. By rotating and imaging it inside an electron microscope it can be seen that these are on the order of 50 nanometres across, but vary greatly in size - some reach up to several hundred nanometres. As is well known, viruses exist everywhere around us, so they are not strange or new but are still nano-objects. So the first picture to capture is that we are immersed in nanoparticles, all around and inside us.

3. Serendipitous nanopigments

Coming back to the question "What do we mean by the history of nanoscience?", this is the story of the serendipitous nanostructure.

JJB works in the field of nano-optics, and everybody in this field shows a picture of the Lycurgus Cup in their presentations – figure 2. This Cup was made in about the 4th century as the earliest known of its kind and is now in the British Museum. It is a form of ruby glass similar to stained glass, where the colour comes from very small, non-spherical chunks of a silver gold alloy that exist inside the glass. The reason it is shown is of course for its beauty. Seen with the light coming towards one (looking through the glass) it looks red, just like stained glass. But seen with light sent from the side and then scattered into one's eyes, the glass looks green. These silver gold alloy nanoparticles scatter green light, so they absorb the red that comes through and scatter the green to the side - clearly that is what the Romans liked about it as well. It is not known if it was made by accident or if one particular technician invented it, but sadly they did not know enough to pass on what they were doing. Like many other things, this technology was lost for thirteen hundred years. When rediscovered it was called the Purple of Cassius after its Roman origins and then became known and used for stained glass across a wide span of space and time.

Figure 2. Roman Ruby Glass.

In fact nanotechnology was used well before that. In about 4500 BC people were already making ceramics containing asbestos nanofibres. Asbestos is dangerous because each crystal is a very thin and short structure that penetrates lung tissue when inhaled, but it was known to strengthen pottery by creating a composite. This could equally be regarded as the birth of nanoscience, but is not the chosen model story.

JJB enjoys telling nanoscience origin stories because optics (that he works on) was there first (or maybe not, as will be seen). The first intentional control of nanoparticle materials was near Mesopotamia around the 9th century and was harnessed to create metallic lustres on glazed ceramics (figure 3). Again the nanoparticles cause different colours to be seen if one looks at the light that is scattered or in reflection. This lustre effect is caused by copper and silver nanoparticles, which are on the scale of about 100 nanometres or below. They can simply be painted on, then glazed and then painted over with another glaze containing metal ions. When heated to 600°C in a reducing atmosphere, the ions migrate to the surface and are then reduced to the metal, forming little clusters. Done with correct technique that formation can be controlled. Clearly there was a lot of practical evidence for the colour formation, but the scientific explanation was not available - nobody knew how it was being produced.

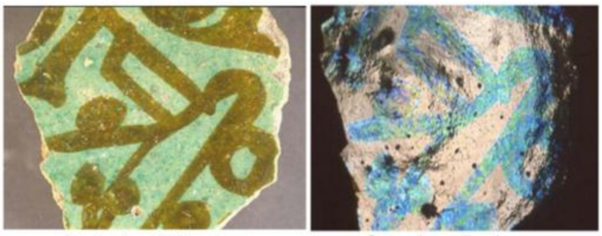

Figure 3. Metallic lustre on glazed ceramics.

4. How to see nano

Interest in seeing materials at smaller scales began the development of microscopy. People found objects under the microscope that move – for example a tiny bead of glass which is not alive will still diffuse. At the time nobody knew what these objects were made of or whether they were alive and self-propelled or just moving because of Brownian motion. In fact on small scales an imbalance of water molecules pushing one side of a particle compared to the another makes it diffuse around.

At this stage in history, one arrives at the point of philosophical confusion. What is living and not living? What animates matter? The idea of animalcules emerged – a word invented by 17th century Dutch scientist Antonie Van Leeuwenhoek (figure 4), referring to small organisms under the microscope. Why were observations of animalcules positively different to how things appear on the large scale? This question was hard to answer until the development of electron microscopy at the Cavendish Laboratory in Cambridge in the 1920s and 1930s. The improving technology resulted in images that really showed what was alive and dead (although though much later in the 1980s there were still discussions about misfolding proteins called prions in the same vein).

Figure 4. Antonie van Leeuwenhoek.

5. Colloids and thin films

In many situations the reported birth of modern nanoscience comes back to Michael Faraday. As well as doing electrochemistry, he started to look at salts of gold. In these experiments he took gold ions and put them in a solution of phosphorus and carbon disulphide, producing various reactions. There is a precursor of a gold ion which gets reduced and the initial straw-yellow colour starts to change into ruby red, the same red that the Romans had discovered – see figure 5. This is caused by tiny chunks of gold nanoparticles, but Faraday did not know this in the 1850s. He just knew that he could see very small spots of light in a microscope, too small to resolve how big they were. This meant they were smaller than the wavelength of light at this stage, so he knew that was at least smaller than about 500 nanometres.

Figure 5. Michael Faraday and gold colloids.

Over centuries this was elaborated on in many ways and has become an enormous area of research. Nowadays within physical chemistry all sorts of nanoparticles can be made with different shapes and sizes which stack in different ways and have different properties (figure 6). Researchers are still arguing about exactly how nanoparticles are formed. Nanoparticles made of gold are just different ways of stacking gold atoms, but how many ways can be conceived of? Not all these ways are possible. There is a long debate in the literature about how these are all being stacked together. We are finally getting to the stage where we can think of atoms as tiny Lego bricks and once at the stage of being able to make objects with tiny nanoLego, one can now think about putting them together.

After the story of gold from Roman times to the modern era there is another story that can be told. This is a story about grinding up things. Already in the late 18th century and early 19th century it was found that chemical reactions could be made to work much better in the presence of certain metals - platinum was found to be a fantastic catalyst. The more the platinum was ground up, the better it got as a catalyst. This is because it is a surface effect, for example if hydrogen molecules are bound onto the surface of the platinum it can then separate more easily into constituent atoms for reactions. In practice if one wants to make a gas lamp that just self-ignites, one simply puts some powdered platinum there – platinum black. When the gas is turned on, the lamp will just come on; it does not need to be lit.

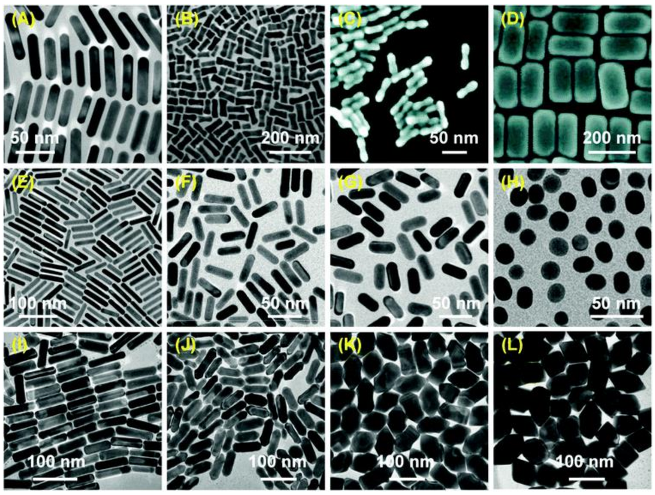

Figure 6. Gold colloids.

This use developed more and more, generating interest in how fine platinum or other materials can be made. In fact this is now central to all of the catalytic converters used in our cars. With 2019 being the year of the Periodic Table, it should be remembered that platinum is one of the 'endangered' elements that is finite and hard to locate. Despite this such nanoparticles are used all the time. Grinding the platinum down helps because the active parts of the surface are just particular facets of platinum nanoparticles where molecules will bind and can then be separated much more easily. Ultimately only greater surface area is needed to make this function work.

Another thing that also merges at the same time with this story is in medicine. There became wider understanding that silver surfaces disinfect objects, although it had been known several hundred years before. In the late 19th century and early 20th century people started to sell silver in colloidal form, similar to that which Faraday produced – figure 7. Argyrol is an example of this. It is stabilised with surface molecules so that the silver does not just fall out of the solution, but remains floating around for a long time. By the 1940s there were perhaps fifty such products on the market that could be bought to disinfect things. Even the Phoenicians apparently stored water in silver vessels so this disinfectant property was not a new aspect that had been discovered recently. The problem thus was that the disinfectant property could not be patented because it was obviously already known. This terminated a lot of businesses, although silver colloids were used to treat everything from gonorrhoea, corneal ulcers and sepsis to tonsillitis.

Figure 7. Argyrol- Silver in colloidal form for commercialisation.

It was Faraday who coined the word ‘colloid’ which means ‘glue’. Lots of scientists discovered uses for these small chunks of metals or matter floating around in solution.

Below follows a story about making thin films because geometry will be very important to this story. A student in the USA named Katharine Blodgett was working with General Electric and she had a very far-sighted supervisor there, Professor Irving Langmuir. He suggested that to progress in the company she should do a PhD and he sponsored her to become the first woman to get a PhD at the University of Cambridge. It was through her refinement of a technique for making thin layers of single molecules on surfaces that got Langmuir his Nobel Prize in Chemistry.

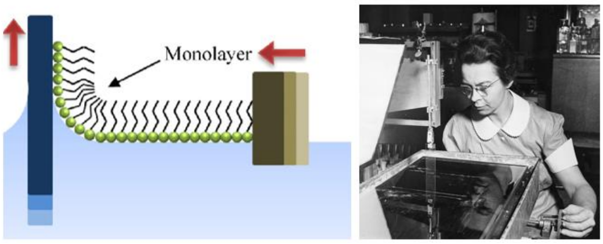

Figure 8. Katharine Blodgett and her discovery.

Her discovery was that molecules could be floated (like a soap bubble) on water and then a single layer could be pulled out on a glass slide – figure 8. This is again science that can be done in the sink at home. A lovely quote from her niece recalls that Blodgett “*always arrived with suitcases full of 'apparatus', with which she showed us such wonders as how to make colours by dipping glass rods into thin films of oil floating on water*”. It was clearly great when someone like this turns up. The niece became a scientist as well.

6. Magnetic nano

Another nano story begins in the mid-1960s with an inventor called Solomon Papell. The problem when starting to make rocket fuel and rockets is that when they get up into orbit the normal fluid dynamics that we are familiar with cannot be used. In a rocket engine on the ground gravity moves the rocket fuel into the engine, but that does not work in orbit where there is only microgravity. NASA got really worried about how they would get things back from orbit, so they tried to invent some magnetic fuels that could still be pumped in microgravity. They found ways to grind up haematite, making magnetic particles that they put in kerosene, a form of rocket fuel. Then they used magnets to pump the fuel into the jet engine – see figure 9 (a).

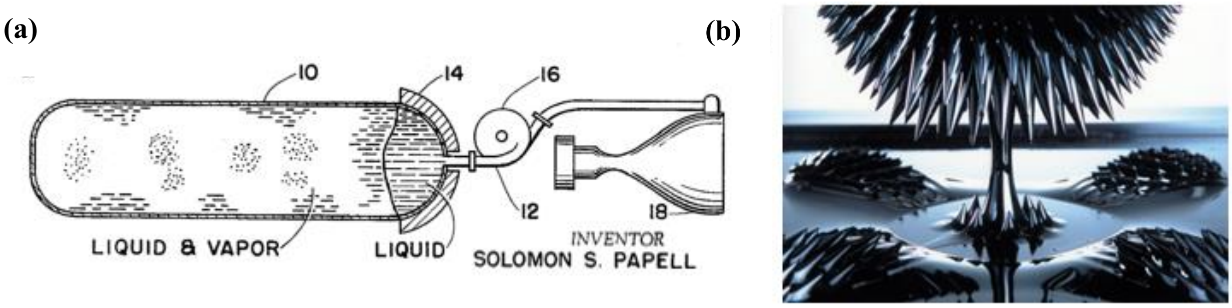

Figure 9. Magnetic particle suspension in fuels.

Nowadays this type of magnetic liquid can be bought – figure 9 (b). Tiny magnetic particles are suspended in oils to keep the particles apart (it does not really work in water). When a magnet is put underneath extremely strange shapes are obtained. The whole fluid wants to reorient to lower its energy and there is a competition between gravity and magnetic forces, producing these strange fluid shapes that completely change with time.

Discussions began about whether magnetism was used in nature at all. In the mid-1970s a scientist named Richard Blakemore was looking in mud swamps. As a good graduate student he looked very carefully at what he retrieved under the microscope. He found a strange bacterial species that had chunks inside them and tried to find out what they were. These chunks are the purest form of magnetic particles that we know how to make – and remarkably they were found in a muddy swamp (figure 10). The bacteria use these to determine which directions are up and down so that they know where to go and find food in different locations. Now it is known that there is a whole group of species that use this to orient themselves on the planet. These bacteria move in the wrong direction if they are taken to the other hemisphere of the Earth – there is a difference between northern versus southern hemisphere versions of these bacteria.

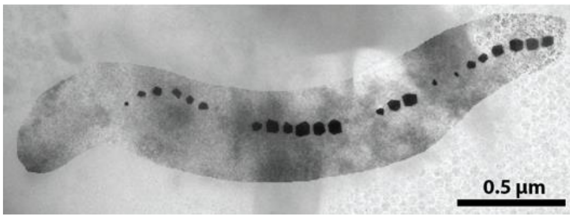

Figure 10. Richard Blakemore's magnetic bacteria.

7. There's Plenty of Room at the Bottom

After many different ways of assembling particles in fluids, one now gets to the first mention of nanoscience and nanotechnology. Richard Feynman is well known already as a theoretical physicist, particle physicist and quantum physicist. During one talk he gave called '*There's Plenty of Room at the Bottom*' at the 1957 American Physical Society (APS) meeting in Caltech, he thought about many different things that could be done on the nano scale. He came up with the idea of 'shrinking Waldos'. Essentially if one does not have a tool to make something small, one instead makes a tool capable of making something a bit smaller, which makes a new tool at a smaller scale to make something ever smaller - a self-replicating pantograph. Feynman knew how to motivate people and Americans of the time in Caltech were particularly motivated by monetary prizes.

In this talk he came up with two challenges: to make a motor that was smaller than half a cubic millimetre or to fit an encyclopaedia on a pinhead. Interestingly Feynman was disappointed with his challenges in the end because within a few years somebody *had* constructed a tiny motor. Bill McLellan, a graduate student at Caltech, did it using completely conventional technology. He just had a good microscope and a very steady hand to wind a traditional motor, and it worked. Meanwhile it took until the mid-1980s before somebody managed to replicate the first page of *A Tale of Two Cities* and actually fitted it on a pinhead.

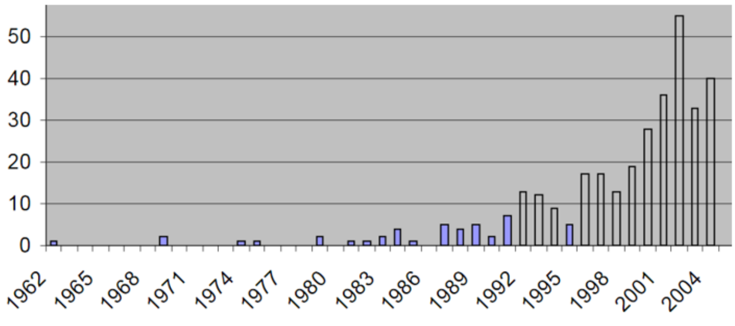

Figure 11. Citation of Richard Feynman's APS talk '*There's Plenty of Room at the Bottom*'.

Everybody mentions this particular talk as the inspiration for nanoscience and nanotechnology, and the problem with all good stories like this is that it is not true. Looking at the citation impact data for this paper (figure 11), after the first twenty five to thirty years nobody referred to it at all, but around 1990 people finally started to take note of it. And why did they take note? They started to be able to work on this nano scale. So it was not until the technology caught up that these visions could have any real impact and they did not spur the way to get to the technology - it worked the other way around.

8. Quantum nano

During progress into work at this scale it was found that very small structures can have some unexpected applications, for example, the semiconductor gadgets used all the time. At the heart of a DVD player is a laser. It is a thin chunk of semiconductor material sandwiched between two others – it is only six atoms across and the electrons are squeezed inside there (figure 12(a)). When electons are squeezed within a region of space, this changes their energy states and it costs more energy to squeeze them more tightly. This is how very efficient light emitters are made now after technology laboratories like Bell Labs invested a lot in this research.

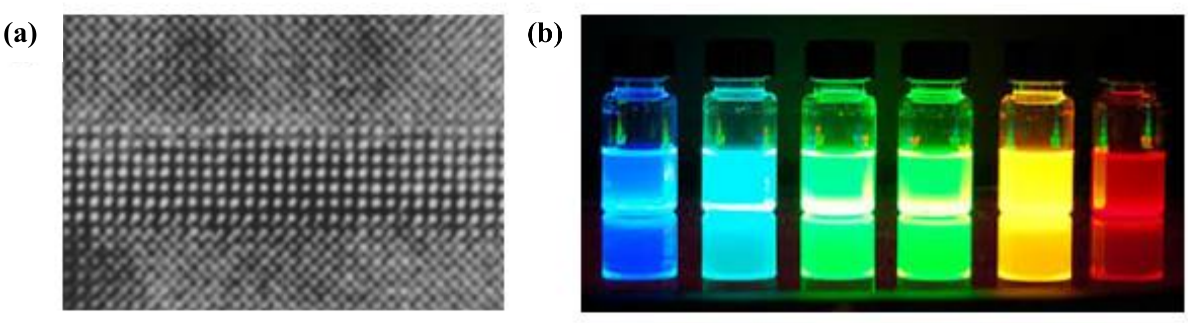

Figure 12. **(a)** Electron-confining layer six atoms thick at the heart of semiconductor lasers. **(b)** Different colours of colloidal semiconductor quantum dots of increasing diameter (2-6 nm) from left to right.

These materials can also grow in solution. One just seeds the growth, lets the tiny particles get bigger slowly and stops it when desired. This makes ‘quantum dots’, small particles of a semiconductor material that emits light. The smaller the particle, the higher the energy of the electron states and therefore the light that can be emitted (figure 12(b)). This is the key connection between nanoscience and quantum technologies because electrons can start to be confined to be a small enough scale that they can be made to do something useful. This has contributed to a series of Nobel Prizes and advances in all sorts of materials physics.

9. Top-down nano

When working with tubes of carbon-based materials and sheets the focus is on getting electrons to occupy different states and to jump around in different ways. This is another story of nanoscience and nanotechnology. On the traditional side all the technology in our mobile phones is based on photolithography – essentially shining light on plastics to make them strong in some places but to dissolve them in others and then depositing sheets of metal like gold. This is how transistors are made that are currently the heart of information storage technology – figure 13. There is an enormous possibility of applications with this, which is what is called ‘top-down’ nanotechnology or nanoscience. One starts with a technological process and then can make things with it, as well as perform experiments on the tiny objects. Not a lot of it is revolutionary, but is closer to evolutionary. Top-down nanotechnology has been going on for the last forty years as we have gradually learned to use these tools and build better ones.

So that is sort of a different type of way of thinking about nanotechnology. It has been shown how to make some of these building blocks, but now one must learn how to put them together to make the exquisite machines found in nature and that is extremely challenging. It is right at the edge of what is possible.

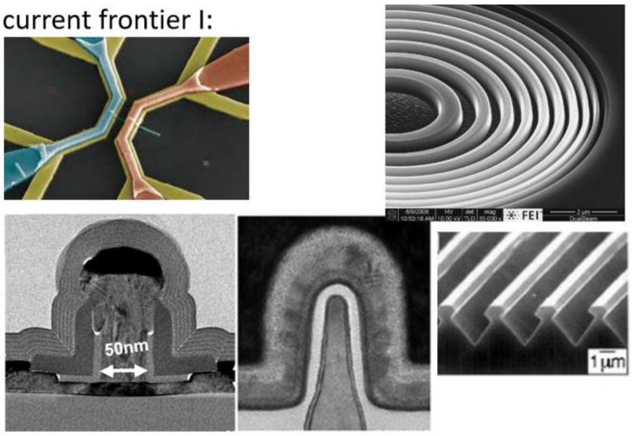

Figure 13. Transistors made using photolithography.

10. Nano-assembly

For instance even putting together a structure as in figure 14(a) is extremely challenging with spheres of one material in another material all uniformly arranged. This is a piece of work that JJB has been doing to make iridescent materials, which has now been commercialised. Lights scatters around in a structure like this in very strange ways and now it can be used in making backpacks. That is all very exciting, but one should hope for something more profound. A current idea is to make coatings on buildings that reduce the heat load by changing colours and controlling what infrared light gets into the building to heat it.

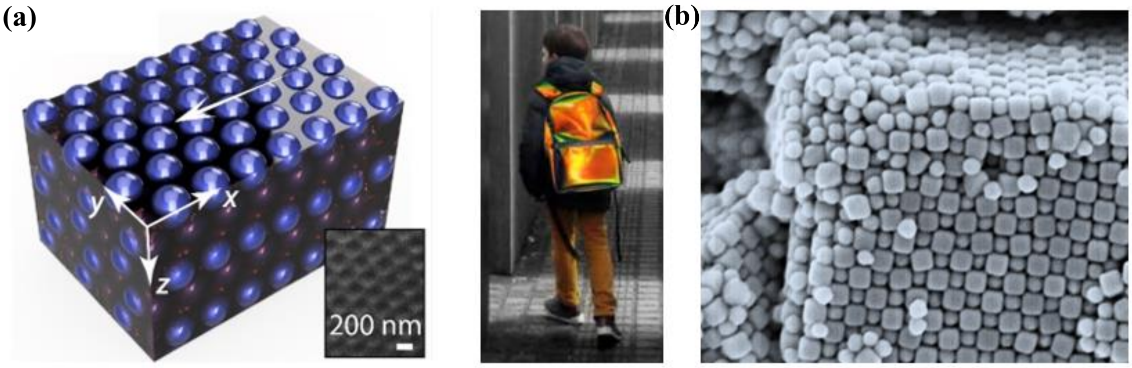

Figure 14. (a) Polymer opals - sub-micron plastic spheres in a perfect lattice act as iridescent flexible materials that can be widely used. **(b)** Stacking of 100 nm-scale cubical and spherical particles of different sizes.

It is emphasised that this is the simplest possible structure that can be imagined - it is like stacking oranges. Even something slightly more complicated like stacking small cubes is not as good – figure 14(b). Anything more complicated than that is extremely difficult. In this area one can borrow from the ideas of nature by taking long lengths of DNA with very precise sequences and learning how to knit them together. Strands of DNA containing half a sequence that will bind to the complementary part of the long strand half are added and then stapled together. Then another twenty or thirty other strands that staple together other bits are added – figure 15. In the end a three-dimensional object like a nano beam has been constructed. There are all sorts of folding mechanisms and ones made that can slot in particles, but this is just a scaffolding. It is not functional in and of itself, but it allows things to be constructed. While not completely cheap yet, it is conceivable now to see how one would get there. This is an area of nanotechnology that is rapidly evolving.

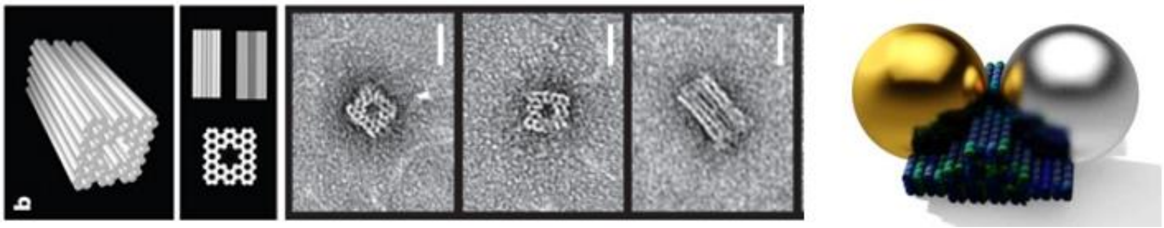

Figure 15. Nano-objects made from knitting DNA molecules into DNA Origami.

11. Where does nano start?

Coming back to the first question 'Where did nanotechnology or nanoscience really start?', one can go back to four billion years ago. Life uses many nanotechnologies but where did this life really start? Biochemists have one idea of a primordial soup. Planetary conditions can create various complicated molecules that form and come apart, but it was not until self-replicating molecules that more profound life appears and moves over to nanoscience - essentially it is when molecules assemble into something that can be encapsulated – figure 16(a). This implies an inside and an outside, and then there can be some sort of selection pressure. If something goes on inside a capsule which is different to the outside, then this can become an entity which is propagated through successive generations. This is the idea of the last common ancestor of all life on Earth.

Figure 16. (a) Concept of 'last common ancestor of all life'. **(b)** Clay platelets which can change catalysis of local chemicals and template new clay platelets. **(c)** Ribosome is one of the complicated machines of life.

Another idea is that clay nanostructures gave rise to tiny plates which assemble into an external structure (figure 16(b)). This would change chemical reactions, say around hot vents under the sea where there is lots of heat and catalysts. Scientists are still arguing about all this because it is not very clear at all. Clearly in here eventually there is very complicated nanomachinery (figure 16(c)), but it must have started out simpler. So in some ways that is one of the answers to 'Where did nanoscience or nanotechnology start?'. It is right back at these first self-replicating systems which are walled off from the rest of the world and that is at least a possibility where evolution can start to hone these structures.

This paper will now discuss three different ways of seeing this sort of history.

12. Competing intuitions

One viewpoint is through intuitions. What seems to be going on at the smaller scale of nano? Researchers at IBM Zurich (and now everywhere) found that a very fine needle was able to push around individual atoms on a surface. Nanostructures could then be made like the iron atoms on a cobalt surface in figure 17(a). Each one of these dots is a single atom pushed into position. Belief in nanoscience and nanotechnology increased after seeing this, and the vision of the field took off.

At the same time the scientist Eric Drexler at a very young age proposed building cogs and machinery out of these structures. Figure 17 (b) shows a simulation of atoms joined together and somehow powered. This is a Drexlerian model of things moving up and down like pistons – figure 17(c). However, it is not this simple. Rich Smalley, a chemist, had an extremely fierce argument with Drexler in the 2000s. Figure 17(d) shows a real simulation of a molecule, a ring moving up and down a long molecule. At this scale in solution this shows that the Drexlerian model is not generally how things work because molecules are 'floppy'. To make things like this there is a worry that there are so many forces going on, one could never turn the wheels in figure 17(b) because it would just break itself apart. When things are made small, they do not stay the same and instead their properties change the way that they operate. Rigidity changes as well. However, it is true that mastering this is not completely impossible in the future.

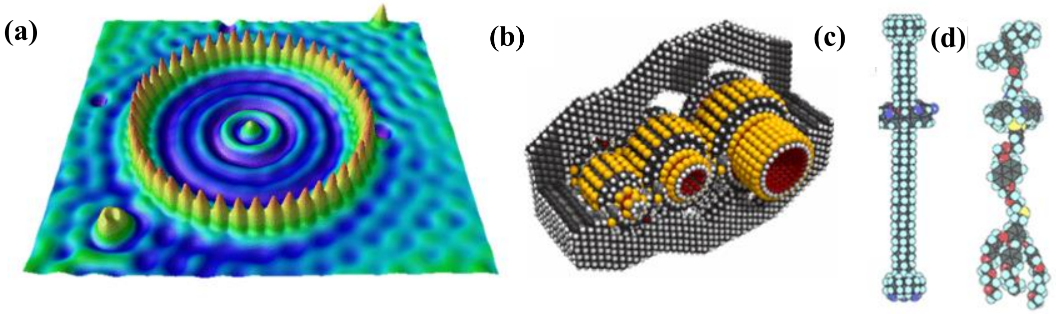

Figure 17. (a) Ring of iron atoms on cobalt surface. **(b)** Drexler model of atomic machine. **(c)** Drexler and **(d)** Smalley models of nano-pistons.

The Drexler-Smalley argument was very interesting philosophically. Figure 17(c) is an engineering approach, while figure 17(d) is a chemistry approach, and in some ways they are just extremes. Making nanomachines with an approach between these extremes is probably possible but as yet unknown. For instance, molecular systems are now being made that self-assemble into cages with pores only a nanometre thick and people will have said a few years ago that this was impossible. So these are very different intuitions, and they are informed and adapt with progress.

13. Narratives of progress

The next way of seeing history is through narratives, where particular examples are selected for each audience - there is no single history book of nanoscience. One has to think about what it might be and invent the stories. One of these narrative histories is about serendipity. Related above was the story of Romans coming across a way to make red/green glass, discovering that it was elegant and then exploring what made it. So humans find something and then explore how it works. That is one way of thinking.

Another narrative is more utilitarian. Figure 18 shows a material discovered in the 6th century BC in the Indian Nadir region - Wootz steel. It was a way of making steel extremely strong. Steel is combined with carbon, then beaten and folded and manipulated, producing incredibly beautiful sheets that have lots of intricate structure even on a small scale. Strength is increased because the carbon goes to the edges of crystallites, locking everything in place. And letting one cut one's enemies' heads off. That is another unfortunate part of human progress and is the basis of Damascus steels – the whole Wootz steel concept was stolen from this advance in war capability. The phrase 'Indian answer' was used by the

Persians to describe ‘cutting straight to the point’ and it came from the amazing hardness property. This is a utilitarian approach, finding a property and then improving it as much as possible; and this also engineers things on the nanoscale without knowing what that is.

Another narrative can be focused on the ‘simplifier’ approach that Faraday followed – ‘How does it work?’. Take it apart, do experiments and eventually one will understand it. This is discussed above. The more recent narrative stems instead from constructing - figuring out how things on this scale can now be *manipulated* – ‘What can be made?’ and ‘What new science, what new technologies can be derived from it?’ But there is no consensus on these different narratives, they are all just different ways of seeing the history of nanoscience.

Figure 18. Damascus or 'Wootz' steel.

14. Visions and contested spaces

Finally, this paper will discuss a very important aspect that often goes unmentioned. That is, science fiction, which appears particularly in technological responses to social crises. In the late 19th century and the first half of the 20th century, this area of fiction began to evolve very strongly. In the 1930s Boris Zhitkov wrote a book called ‘*Microhands*’ – figure 19(a). He was an explorer, a teacher, a scientist and an engineer in a workshop and he was very critical of the Soviet regime. His story was built on the idea of tiny little hands for construction. Robert Heinlein furthered this idea in his book ‘*Waldo*’, exploring making things on a tiny scale by shrinking everything down – figure 19(b). In fact this is what Richard Feynman referred to in his talk - the idea of Waldos and the shrinking pantograph. One makes hands that make smaller hands that make smaller hands and so on. When he first published it, Robert Heinlein was embarrassed enough about this idea to use a pseudonym, Anson MacDonald, but then it became popular.

Then other writers moved into the science fiction scene like Arthur C. Clarke, who wrote a short story called ‘*The Next Tenants*’ where he discussed how the human race was going to destroy itself – figure 19(c). He felt that the best idea was to educate the termites to take over as they have been around the longest. The story is all about how one could give tools to termites, which of course is now a technology under research using ant behaviour studies. Beyond this there were lots and lots of stories emerging in the 1960s and the 1980s, talking about how nanoscience might be used.

A pattern often found is that nanoscience and nanotechnology are often explored in fiction first. Fiction is far ahead. When some new science is produced, it is often asked, “Hasn't that been done already? I am sure I read about that”. It is sometimes rather annoying because of the public’s frustration that we are so far behind what is possible that imaginations run wild and do not realise the impact of what we *can* do now.

Then arises the problem of where to credit the history. Is it the visionary idea, the fact that Feynman had these ideas although they were just completely unfeasible at the time? Or must we credit the practical progress made after him? The hard graft and the many inspirations to invent new ideas and concepts that work on the nano scale. Visionary ideas often come from the science fiction stories, but is science fiction really the progress, the idea of it? The idea of a Gedankenexperimentor 'thought experiment' came out in the 1920s and was extremely important in stimulating scientific thought. Some suspect that within this myth of the origin people use Feynman because he was really a good intuitive scientist and he talked about nanoscience, so therefore people thought "It has to be a valid subject!". Scientists bask in the greatness of the great but it is not a very solidly-based way of justifying what we do. Science has areas which are trendy and areas which are not trendy, but in difficult areas you just need to keep on progressing and have faith in going different directions. Often people will say, "Oh, that's just chemistry, that's not nanoscience" or "That's just engineering, it's not nanoscience" but there is no definition of nanoscience. Nobody agrees on it. So the current issue is about who gets to police these boundaries.

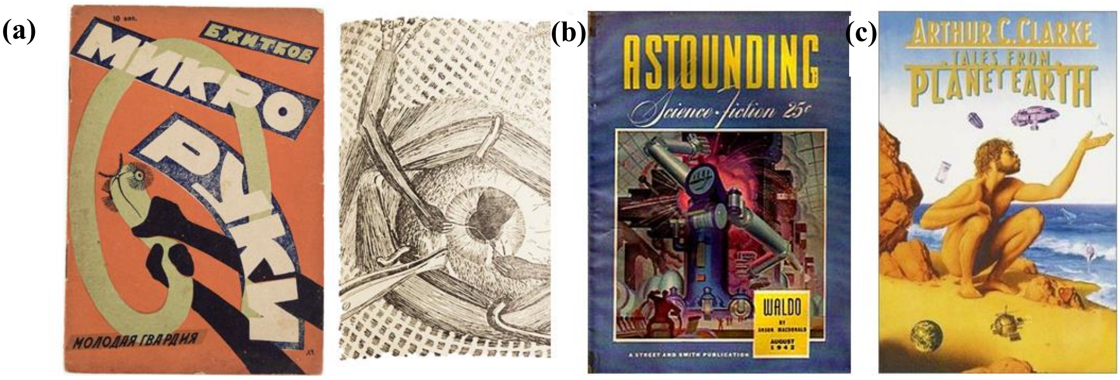

Figure 19. (a) Cover and illustration of Zhitkov's *Microhands*. **(b)** Cover of Heinlein's *Waldo* story. **(c)** Cover of Clarke's *The Next Tenants* story.

It is always the winners who write history and it is not very clear in this case who are going to be breakthrough winners for nanoscience. Is it the people who are adopting some biological approaches or top-down approaches or a whole mixture of them building things from origami? It is completely unclear so far. That is as much as can tell be said really about the history of nanoscience. There is not one. There is a whole range of different stories and you can choose whatever you like!