1
Quick – Name Something "Nano"

Quick – name something "nano."

Name something that occurs at the nanoscale – a structure or process that we measure in nanometers. One nanometer is a billionth of a meter. Nanoscale refers to 100 nm or less. So name something under 100 nm.

As a manager, you should be able to name at least one or two things that are nanoscale. Can you do it? How quickly?

Are you still thinking? Do you have it? Are you *sure* that's a nanoscale example?

Okay. Let's make it easy. Name something nano that occurs naturally in the human body.

What did you say? A human hair? A blood cell?

Wrong.

A human hair is 50 000–80 000 nm thick. A red blood cell is about 2000–5000 nm. A white blood cell is about 10 000 nm in diameter. The period at the end of this sentence may contain 1 000 000 nm of ink.

Think smaller. Much smaller.

Can you name *one commercial product* that uses nanotechnology? This could be something that contains nanosized particles or nanomaterials. Here's a hint: You can find a nanotechnology product in almost any gift shop on the beaches of Cancun, Florida, California, or the French Riviera.

What about man-made nanostructures (Figure 1.1)? Almost any nanotechnology article talks about carbon nanotubes, the popular building blocks of nanotechnology. Can you name one product that uses carbon nanotubes?

Here's one example – most automobiles use carbon nanotubes in engine coatings because their semiconducting properties make nanotubes ideal for controlling static electricity or sparks that might cause a fire or explosion. Nanotubes are also mixed with polymers in seat covers so that you don't get a shock when you slide behind the wheel on a cold winter day. Carbon nanotube fibers are so incredibly strong and durable that they are used to strengthen military body armor.

Nanotechnology is used in an incredible variety of products, processes, and applications. Your tablet computer and smartphone use nanoscale circuits. Your flat screen TV is thin and lightweight, thanks to nanomaterials. Nanoskins protect antique buildings. Edible nanoskins protect apples and other fruits, and

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allow the last drop of ketchup to slide out of the bottle – although most food manufacturers are being highly secretive about their use of nanomaterials, having been spooked by the industry's experience with genetically modified foods.

Nanomaterials protect your pants against stains, liquids, mildew, and wrinkles. A nanofiber pocket in your shirt or jacket can screen the radiation from your cell phone. Athletes can buy no-smell socks infused with nanosilver particles that eliminate odor-causing bacteria. Other applications include clothing that changes color in response to light or body heat.

Many clothing items use technology developed by NanoTex, a US-based company that uses nanotechnology to develop "intelligent fabrics."

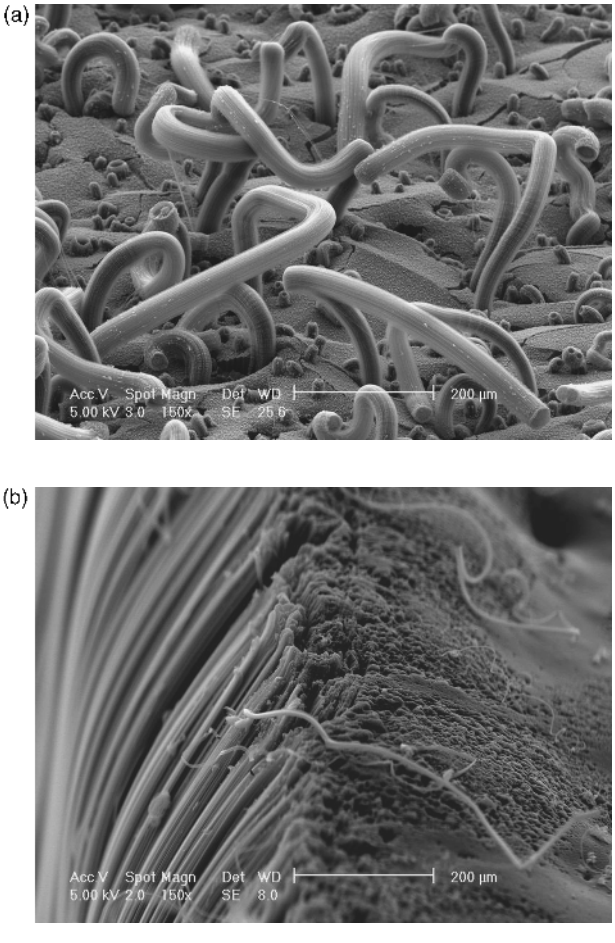

Figure 1.1 Carbon nanotubes that are 1 or 2 nm in diameter can be grown on a substrate as a tangled "forest" (a), made to grow in tight clusters (b) and formed into complex shapes and patterns, using photolithography and catalyst patterning (c). Shown here is the first nanoscale image of a world leader – President Barack Obama. Each Obama face contains 150 million nanotubes (images by Anastasios John Hart, University of Michigan).

(c)

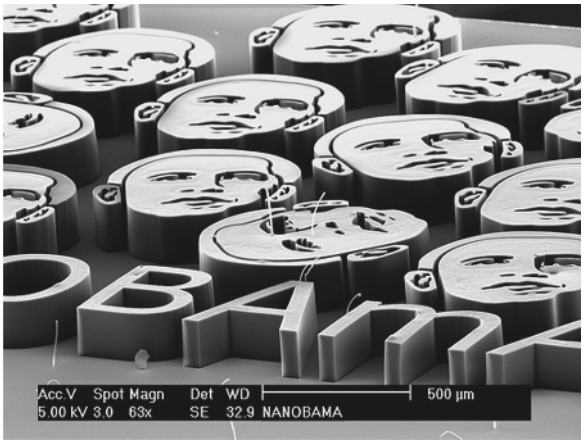

Figure 1.1 (*Continued*)

A few years ago, Philips Lighting created a lot of buzz at the Consumer Electronics Show by demonstrating a jacket with light-emitting diode (LED) optics woven into the fabric. The jacket displayed an animated message – suggesting that wearable computers may be closer than we think.

Another area that we all benefit from involves *catalysts*. Unless you're a chemist, you may not get too excited about catalysts – but think about this: catalysts are a *$100 billion business*.

Historically, catalysts have been used for millennia to strengthen steel, create new materials, and facilitate chemical processes. Today, most metal and plastic products are created using catalysts. Many of these processes have not changed for 100 years, so this isn't a sector where you'd expect to see a dramatic improvement, or radical innovation. However, nanosizing a catalyst can produce dramatic improvements. If you fill a basketball with nanoparticles, those particles will have more surface area than a basketball – that's the secret. Using smaller particles means you need less material to achieve the same catalytic effect – a competitive advantage if the catalytic material is an expensive rare earth element. But what about more common products – maybe a common household product like *ammonia*?

QuantumSphere Inc. (QSI) is a small company based in Santa Ana, California, that makes metal spherical nanocatalysts. Kevin Maloney, president and CEO, explains how a chemical as common as ammonia is benefiting from nanoinnovation. "Most of us think of ammonia as a household cleaner," he explains. "But most ammonia is used for food production and biofuel feedstocks. Fifty percent of all protein consumed comes from ammonia. There are about 400 plants worldwide that produce ammonia – so much that ammonia production and related processes consume as much as 2 percent of the world's annual energy supply and generate 1.6 percent of global CO_2 emissions."

The Haber–Bosch process used to produce ammonia was invented in 1909, and involves combining nitrogen and hydrogen gases over a heated, pressurized bed of iron. There hadn't been a breakthrough in this process for more than a century. QuantumSphere developed a patented process to improve the process using a nanocatalytic form of iron.

"Early in our research we demonstrated a 26 percent increase in yield," Maloney recalls. "We realized that this could translate into a significant improvement in commercial production, as well as financial and energy savings for the ammonia industry." Today, QuantumSphere is working with the leading producer of ammonia reactors to commercialize their process. The "business story" of QuantumSphere is described in more detail in Chapter 6.

This is a great example of a nanoinnovation with enormous potential impact that is happening largely out of sight. An energy-efficient, economical improvement in ammonia production may not be considered "radical" or "disruptive" by most of us, but if you're in the agriculture, biofuels, or ammonia industry, this could be a high-impact, radical innovation.

Radical Nano and Killer Applications

While these applications are important, they are not exactly radical. Most of these innovations have been creeping into products as incremental improvements to enhance functionality, replace or reduce materials, lower production and processing costs, and minimize negative effects. The first waves of nanoinnovations are so embedded in everyday products and processes that we don't give them much thought. There is no "nano inside" label on your car engine or laptop. Most consumer products that use nanoparticles do not list "nano" on their labels (although this is changing).

Most of the "killer apps" from nanoinnovation are still being developed, which makes this an ideal time for you as a manager to start learning about nano.

As Mark Banash, Vice President and Chief Scientist at NanoComp puts it, "There aren't a lot of killer applications yet for nanotechnology, but there are some 'assassin apps' that are replacing existing materials in the form of structural composites, multi-purpose materials, and more efficient catalysts. A lot of substitution is already taking place, and in the future we can expect a lot more."

Mark is in a good position to know. In February 2008, NanoComp set a record for the world's largest sheet of carbon nanotube material (Figure 1.2). Mark observes that carbon nanotubes are less than half the weight of comparable aluminum. Yarns and sheets made from carbon nanotubes possess a unique combination of high strength-to-weight ratio, electrical and thermal conductivity, and flame resistance that exceeds other advanced materials.

The question is, what will product developers actually do with these new materials? What can you wrap in a material that is one or two atoms thin but as strong as metal, as flexible as cloth, and able to provide electrical and thermal conductivity, flame resistance, and more? Will you integrate it into the uniform of a soldier or firefighter, or wrap it around a car, a house, or an office building? Also, will the ultimate "carbon nanosheets" be made from a composite made

Figure 1.2 Nanocomp's 3′ × 6′ sheet made from carbon nanotubes set a world size record. The company is refining processes to manufacture these sheets, which can be up to 100 times stronger than steel, in commercial quantities. Shown here is Nanocomp technician Jeff Littlefield (who is 6′ tall) lying next to a sheet of the material (photo courtesy of Nanocomp Technologies).

with nanotubes and carbon fibers, entirely from carbon nanotubes, or from single or layered sheets of graphene or graphane?

Professor John Hart's team at the University of Michigan-Ann Arbor predicts a day when nanopores in nanoskins will regulate the flow of air, moisture, and heat in buildings without any mechanical controls. He says, "We know this is possible because we're doing this now in the lab."

There are lots of radical innovations in research laboratories that could be called game changers – digestible nanocomputers that can fit inside a pill, hollow nanospheres that can deliver drugs inside individual cells, and composites that make metals as flexible as plastics, and allow plastics to conduct electricity.

Nanopool GmbH, a family-owned business based in Schwalbach, Germany, has announced the development of liquid glass, an ultrathin form of SiO_2 (the *chemical notation for silicon oxide, which is glass*). Liquid glass can be sprayed on any surface to create a 100 nm coating that is both flexible and breathable. The coating is about 500 times thinner than a human hair, and is invisible to the eye. What is most interesting about this material is that no nanoparticles are added – according to the company, the coatings form and bond due to quantum forces, which suggests that this nanocoating could be safe and inert enough to use to coat hospital surfaces, kitchen sinks, industrial machinery, even textiles, and medical implants. The easy clean nature of a glass coating could greatly reduce the amount of toxic cleaning agents now used to clean and sterilize surfaces in hospitals, homes, and industrial clean rooms. Because it is breathable, it could be sprayed on stone, brick buildings, or statues to help protect against pollution.

What makes nanotechnology so exciting is its potential to solve problems in new and different ways that were impossible and unimaginable just a few decades ago. And that's why you need to know more about nanoinnovation. As a manager, you're in the business of solving problems, creating value, and turning ambiguous situations into something tangible. Nanotechnology holds incredible potential – this can take the form of an improvement, a breakthrough, a competitive advantage or a competitive threat. A breakthrough innovation in one company can be a death blow to another. In a world where open innovation and global networking is already transforming industries and markets, you need to know about nanoinnovations that are looming on the near horizon.

As a manager, you should be able to name one or two examples of nanoinnovations that could change the future. For example, what are scientists working on now that will really shake things up if they succeed? Can you name one area of science where nanoinnovation is playing a critical role?

The Science on "Planet Nano"

My wife Nancy, a medical researcher and nursing student, likes to describe science as a puzzle – all you have to do is solve it, she says.

I like to think of nanoscience as a new frontier. In many ways, innovating at the nanoscale is like exploring an entirely new planet – Planet Nano. The features of this planet are truly "alien." On this planet, objects don't behave like they do in our human world, at our familiar human scale.

At the nanoscale, water becomes sluggish and doesn't flow. A carbon molecule can be made to conduct electricity – or not. Metal has "memory" and can snap back to its original shape. Biological structures warp and flex into odd shapes and sizes. Synthetic DNA can be formed into pyramids and boxes. Stem cells are sprayed on scaffolds using inkjet printers to regenerate human organs. These are only a few examples of what we see when we peer into the nanoscopic world.

The science that drives nanoinnovation is not limited to research laboratories. There are conceptual thinkers like Robert Freitas who conceived – and patented – the artificial blood cell and numerous other innovations, and Eric Drexler, whose seminal concepts of molecular manufacturing generated both enthusiasm and controversy.

Some of the most impressive innovations will come from the *convergence* of unrelated materials, processes, and applications. Convergence has always been a major driver of innovation. In the past, a great deal of convergence came from "eureka" discoveries and serendipity. Nanotechnology is giving researchers the tools to *engineer* convergence (Figure 1.3). By any metric, this is a sea change – one of the most intriguing aspects of nanoinnovation. Instead of accidental convergence, or convergence that comes from decades of experimentation and fortuitous discovery, nanotechnology is allowing us for the first time to manipulate atoms and molecules to create solutions that can only be achieved at the nanoscale.

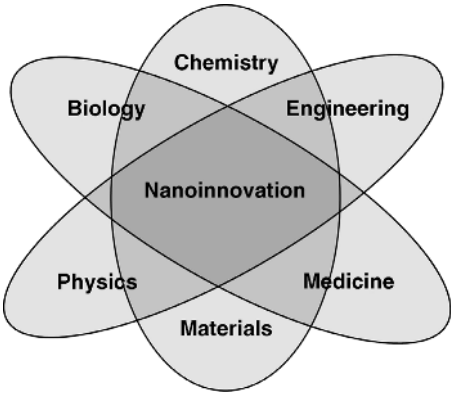

Figure 1.3 Nanoinnovation enables "engineered convergence" at the intersection of the major areas of science and technology.

Many nanoscience innovations sound like science fiction, but they actually do exist. For example, there are nanomaterials that allow electronic devices to twist and stretch and curl – and resume their original shape. Nokia has demonstrated concept phones that change shape when a call is received (Figure 1.4).

The military is developing invisibility cloaks to conceal tanks and submarines from enemy radar – or make soldiers invisible to the naked eye. Researchers have

Figure 1.4 Nokia's Morph concept phone uses nanotechnology to give the cell phone a new form factor that includes "shape shifting" (image courtesy of Nokia).

created mechanical insects that can "fly and spy" and swarms of weapons that resynch and keep functioning even if part of the swarm is destroyed – similar to the nefarious nanoswarms depicted in Michael Crichton's classic novel *Prey*.

In 2013, the US Army's Special Operations Command announced a program called TALOS – Tactical Assault Light Operator Suit – a futuristic combat suit made from lightweight advanced materials and nanoelectronics that the Army hopes to deploy by 2018. TALOS will be worn as an "exoskeleton" that includes such functions as portable power, health monitoring, climate control, biohazard filters, mobile communications, targeting systems, and weaponry.

In the energy field, research teams are working to shrink a complete solar cell to the size of a nanoparticle so that solar cells can be painted on a building or a rooftop. Medical researchers have developed molecular structures made out of gold and boxes made of synthetic DNA that can deliver drugs to cancer cells like nanoscale UPS couriers. This is not science fiction. These are real projects being developed by real people. These nanoscience projects are of special interest because the first wave of nanobusiness ventures came from university science projects and the next wave is being worked on by scientists in every region of the world. The next game changer could come from Silicon Valley or Rice University, from the Biopolis in Singapore, a nano consortium in Europe, or a university in Shanghai or Mumbai. Virtually every large corporation has a nano research laboratory and every major government and industry has a nanotech road map.

Safety Issues: Can Killer Apps Really Kill?

Of course, there is another side of nanoscience that needs to be considered, including the impact of nanomaterials on health, safety, and the environment. There is evidence to show that some "killer applications" could really kill – if nanoparticles find their way into our lungs or other organs where the accumulation of foreign substances can cause cancer. Nanoparticles and fibers have already been shown to sever DNA strands, which can trigger cancer. Longer fibers such as "long carbon nanotubes" have been compared with asbestos fibers that are lethal. Silver ions are natural bacteria fighters used in everything, from medical equipment to washing machines. They can also destroy friendly bacteria and are potentially harmful to aquatic life in streams.

These issues are still being studied and have yet to be resolved. However, as regulatory agencies seek to err on the side of caution, we can definitely expect more "nano inside" listings and warnings on product labels. And of course, safety issues – especially a potential "killer" in some killer applications – raise the stakes for business investors and companies. These risks and uncertainties need to be weighed along with the potential profits of nanoinnovation, which of course is considerable and hopefully worth these risks.

The Business of Nano

Nanotechnology is poised to generate a trillion dollars in revenues worldwide. Economically, the nanoscale business revolution will be as powerful and ubiquitous as the digital revolution. Its impact will be as transformative as electricity and the

power grid, the modern highway system, or air travel. But this won't happen overnight. The nanotechnology infrastructure is still forming. Universities and companies are racing to catch up to the need for nanotech scientists and engineers. Companies are still trying to identify their research goals and business strategies.

In the next decade, the most successful companies and institutions will need to become *nanodextrous* – able to work at the nanoscale with the same confidence and proficiency they now work at the macroscale.

Despite strong expectations that nanoinnovation will provide substantial value to customers, companies, and investors, there is also a great deal of uncertainty. Some of these uncertainties are easy to identify, but their outcomes cannot be reliably predicted. To help understand these uncertainties, we can compare nanoinnovation with analogous examples from other technology-driven industries and markets such as the Internet, gene therapy, and genetically modified foods.

Even the most successful technologies and products need to cross the chasm between the laboratory and the marketplace – what some people call the "valley of death." When nanoinnovations first began to appear, there was a concern that some markets might shun nanoinnovations like Europeans initially shunned food products made from genetically modified crops.

Another concern was whether the multibillion dollar investments in nanotechnology research would justify the investment. Gene therapy has soaked up more than a billion dollars in research funding and investment, and generated enormous hype – and hope – but without one major commercial gene therapy available more than a decade after the human genome was mapped. Will nanoinnovation take decades to commercialize like gene therapy?

We know one thing – the commercialization of nanotechnology is already well underway. Many industries have already included nanotechnology in their products, so the question about commercialization is moot. Nanoinnovation will not follow the same course as gene therapy.

Will nanoinnovation emulate the experience of genetically modified foods? It's difficult to predict, but current indications are that nanoparticles and nanomaterials have a few more years of free reign before they are rigorously analyzed, tested, regulated, labeled, and verified as totally safe. Some consumer products have already come under scrutiny; however, there is still no firm consensus on several important safety issues. Will nanoparticles breathed in by workers or customers be treated as harmless elements by the body – or lurk for years or decades as a slow and deadly killer, like cancer-causing asbestos?

Of course, any new technology sector faces business risks. Will business managers, including scientist entrepreneurs who are not schooled in management *per se*, make the same mistakes as the hundreds of Internet ventures that went bust in the 1990s? As a manager, you may be in a position to influence decisions to invest in, develop, deploy, or market nanoinnovations.

Who is Driving Nanoinnovation?

One of the most intriguing aspects of innovation is who's doing the innovation? Most nanopioneers were not trained as nanotechnologists, simply because there

were no nanotechnology courses when they got started. Most are self-taught and come from eclectic backgrounds that range from biology and medicine to computer science, from catalytic and crystallography to electronics and mechanical engineering. These pioneers include a generous representation of business entrepreneurs and venture capitalists who were attracted to nanotech because they saw this as the "next big thing" in emerging technologies. Many had to create their own opportunities because there was no infrastructure when they started their research. Here are just a few examples of some notable nanoinnovators you will meet in this book.

Shane Woody and his wife Bethany built their own atomic force microscope while still in college. Today they own a profitable enterprise called InsituTec that manufactures and sells nanoimaging systems, and also does cutting edge R&D.

Nadrian "Ned" Seeman is a bearded, congenial chemistry professor at New York University who founded the field of structural DNA nanotechnology. Ned has been pioneering the use of DNA to build structures for more than 30 years. He recalls that when he started the field more than two decades ago, he was the only researcher doing this. Today, he estimates that more than 50 research teams are working in the field he pioneered.

Another DNA pioneer is Paul Rothemund, a senior researcher at Caltech who is famous for a type of structural DNA called "DNA origami." Dr. Rothemund is famous for creating a smiley face and other familiar images out of DNA. He has written thousands of words explaining and evangelizing DNA origami, so researchers around the world can learn and contribute to this research.

Han Cao, founder and chief scientific officer at BioNano Genomics (formerly BioNanomatrix), is doing something very different – but equally compelling – with DNA. Dr. Cao has learned how to tease single strands of DNA into unraveling and moving through channel on a nanofluidic chip. He watches as a strand fluoresces – able to see the glow with his naked eye. This is the first device that can isolate and image very long strands of DNA molecules.

Dr. Andrew Thompson, the glib English born cofounder and CEO of Proteus Digital Health, is leading a team that pioneered what he calls "intelligent medicine" – including a biochip sensor made of ingestible components that can be embedded in a drug capsule or pill to monitor whether a patient has taken the prescribed medication as required. This "chip on a pill" is depicted on the cover of this book.

Jim Von Ehr is the founder of Zyvex Corporation, the first molecular nanotechnology company. Jim began as a software pioneer. He was the founder of Altsys, a software developer acquired by Macromedia in 1995. Jim leveraged his success into a large personal investment in nanotechnology, where he has been pushing innovation frontiers on several fronts, from instruments to molecular manufacturing.

These are only a few of the more than 150 nano insiders who generously shared their personal stories for this book. Their insights into nanoinnovation and where the future may lead us are truly fascinating and hopefully will help you shape your own strategy.

So how does all this relate to you as a manager?

I started this book by challenging you to "name something nano." If you want to participate in the nanoscale revolution at any level, everything starts with this simple question. But there are lots of other questions that you as a manager need to be able to answer. You may have some of these answers already. Let's start by finding how much you know – or don't know – about nanoinnovation.

Your Nano I.Q

How much do you know about nanoinnovation? Most of us – myself included – don't know as much as we think we do. Here's a short 20-question quiz to test your "Nano I.Q." I.Q. normally means "intelligence quotient," but here it means "innovation quotient." This is not a formal test, just a fun exercise to get you started to see how much you know (or don't know) about nanoinnovation. You'll find the answers to these questions scattered throughout this book – or you can jump to Appendix A that provides the answers along with some additional notes.

1. Which of these consumer products use nanotechnology?
   - ☐ Dockers jeans
   - ☐ Sunscreen
   - ☐ Toyota Prius
   - ☐ Computers and cell phones
   - ☐ All of the above
2. In 2014, approximately how many consumer products used nanotechnologies (according to the Project on Emerging Nanotechnologies of the Woodrow Wilson Center)?
   - ☐ <10
   - ☐ 100
   - ☐ 560
   - ☐ 1300
   - ☐ >1800
3. The term "nanotechnology" was first coined by
   - ☐ Richard Smalley
   - ☐ Norio Taniguchi
   - ☐ K. Eric Drexler
   - ☐ Richard Feynman
4. This Nobel Prize winning scientist gave a lecture at Caltech in 1959 entitled "There's Plenty of Room at the Bottom" – setting the scientific community on a course of discovery that gave rise to the field of nanotechnology.
   - ☐ Richard Smalley

- ☐ Carl Sagan
- ☐ K. Eric Drexler
- ☐ Richard Feynman

5. The scanning tunneling microscope capable of imaging the nanoscale was invented in
   - ☐ Germany
   - ☐ Japan
   - ☐ Switzerland
   - ☐ The United States
6. What was the first recognizable image created by manipulating individual atoms?
   - ☐ The IBM logo
   - ☐ A Mickey Mouse cartoon from 1929
   - ☐ The yin and yang symbol
   - ☐ A yellow "happy face"
7. The first US president to have his image rendered at the nanoscale is
   - ☐ George W. Bush
   - ☐ William Clinton
   - ☐ Barack Obama
   - ☐ Ronald Reagan
   - ☐ None of the above
8. Nanoparticles of gold (below 100 nm) are what color?
   - ☐ Gold
   - ☐ Silver
   - ☐ Red or purple
   - ☐ Black
9. Nanoparticles of iron oxide – called "nanorust" – can be used to
   - ☐ remove bacteria from washing machines
   - ☐ desalinize seawater
   - ☐ remove toxic arsenic from water
   - ☐ kill cockroaches
10. Buckyballs and nanotubes are forms of
    - ☐ gold
    - ☐ silicon
    - ☐ carbon
    - ☐ semiconductor circuits
11. Which country holds the most nanotechnology patents?
    - ☐ Japan
    - ☐ Germany

- ☐ India
- ☐ South Korea
- ☐ The United States

12. Which country is the nanotechnology research leader in Latin America?
    - ☐ Argentina
    - ☐ Brazil
    - ☐ Chile
    - ☐ Mexico
    - ☐ Uruguay
13. Which of these atoms is larger than 1 nm in diameter?
    - ☐ Oxygen
    - ☐ Cesium
    - ☐ Uranium
    - ☐ All atoms are >1 nm
    - ☐ All atoms are <1 nm
14. Which of the following has been created by scientists in nanotech laboratories?
    - ☐ A nanoscale box with a lid, made of synthetic DNA
    - ☐ A paper battery that you can fold or cut
    - ☐ A hollow gold nanosphere capable of delivering cancer fighting drugs
    - ☐ Carbon sheets one atom thick
    - ☐ All of the above
15. Does Europe spend more or less than the United States on nanotechnology research?
    - ☐ More
    - ☐ Less
    - ☐ Approximately the same
16. Which of the following is an example of nanoinnovation?
    - ☐ High-performance baseball bats and golf clubs
    - ☐ Flexible thin-film solar cells
    - ☐ Digestible computers for tracking pills
    - ☐ Cell phones that bend and twist like plastic
    - ☐ All of the above
17. Which of the following are nanoscale (<100 nm in diameter)?
    - ☐ West Nile Virus
    - ☐ Red blood cells
    - ☐ White blood cells
    - ☐ Human hair
    - ☐ *Escherichia coli* bacteria

18. The world's largest carbon nanotube manufacturing facility is located in which country?

    ☐ Germany
    ☐ The United States
    ☐ Japan
    ☐ China
    ☐ India

19. Which of the following companies holds the most nanotech patents?

    ☐ Fujitsu
    ☐ GE
    ☐ IBM
    ☐ Nantero, Inc.
    ☐ Siemens

20. Which products in Europe are required to identify nanosized ingredients with the word "nano" in brackets?

    ☐ Food products sold in supermarkets
    ☐ Cosmetics
    ☐ Candy
    ☐ Clothing
    ☐ All consumer products