The Royal Academy of Engineering

International Lecture

Future Technology Horizons

Speaker: Dr Craig Barrett, Chairman, Intel Corporation

9 March 2006

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INTRODUCTION

Lord Broers, FREng FRS
President, Royal Academy of Engineering

It is my very great pleasure to welcome you here this evening for the Academy's inaugural international lecture. Innovation of course takes place on a global stage and it is perhaps surprising that the Academy has not previously had an international lecture, so this is a history-making moment. This series will fill an important gap by allowing a UK audience to hear an international perspective from an eminent person in the broad field of electrotechnology.

The emphasis of the subject area reflects the interests of the ERA Foundation, the Electrical Research Association, which, in 2004, made a generous donation to the Academy which has made this lecture series possible.

The choice of speaker for an inaugural lecture is always a difficult task but the Academy's selection panel, led by Peter Saraga, our Honorary Secretary for International Affairs, was clear in its view and for very good reasons. Its unanimous choice was for Dr Craig Barrett, Chairman of the Board for the Intel Corporation.

For decades, Intel has developed technology enabling the computer and internet revolution that has, quite literally, changed the world. Founded in 1968 to build semiconductor memory products, Intel introduced the world's first microprocessor in 1971. Intel is the world's largest chip maker and is also a leading manufacturer of computer networking and communications products. Much of Intel's success is due to our speaker tonight.

Dr Barrett's achievements in the 32 years he has been at Intel have been immense. In addition to providing leadership, he has written over 40 technical papers dealing with the influence of microstructure on the properties of materials and a textbook on material science. He has been appointed to the President's Advisory Committee for Trade Policy and Negotiations and, as chair of the US National Academy of Engineering, Dr Barrett shares a common concern with all of us present tonight: the need to promote excellence in engineering and inspire the next generation.

Part of the Royal Academy of Engineering's *raison d'être* is to celebrate and learn from excellence in the engineering community. It is a great pleasure, therefore, to introduce Dr Craig Barrett this evening. [*Applause*]

THE DIGITAL EVOLUTION

Dr Craig Barrett
Chairman, Intel Corporation

It is a pleasure to be here: thank you for that kind introduction. I appear before you tonight as a representative of both Intel and of the National Academy of Engineering in the United States, of which I have the honour to be chair. Let me say at the outset that there are a great many similarities between our two countries, and our professions in our two countries. We face some of the same challenges and some of the same opportunities. Tonight, I would like to focus a little on the opportunities and perhaps say a few things about the challenges that we face. I repeat, it is an honour to be here for this inaugural international lecture.

Engine of change

I want to talk about the technology that our company deals with, which is digital technology and digital electronics. I would suggest that you really have not seen anything yet in this field. The transistor was invented approximately 50 years ago and the first integrated circuit perhaps 40 years or so ago. These have had a profound effect on everything around us and I would hope to convince you that the changes that we have seen are startling, but the changes that we will see in the next 10 or 20 years will be equally so.

I will talk a little about the base technology and then say a little about innovation from a national level. At the end, I will try to give you a few insights, after 32 years at Intel, about what works and does not work in terms of promoting innovation – taking groups of smart people and giving them several billion dollars of research funds, to see what you can accomplish. I used to think that $1 billion was quite a large sum. When I first came to Intel, I had been teaching at Stanford prior to that, where my idea of Nirvana was to have a research budget of a few hundred thousand dollars each year and half a dozen graduate students. I used to wonder what more one could ask for, other than perhaps $50,000 a year to buy capital equipment but that does not even make the rounding error for one day's investment at Intel at present: I think we will do $6 billion of R&D this year. The bottom line, however, is that technology is still alive and well and exciting, and we will talk about that.

Engine of change – Global Opportunity

Part of my job, as chairman of the company, is to worry about international development. I have the opportunity to travel to about 30 different countries each year and, in those countries, I usually spend time with business leaders, government leaders and academic leaders. I am very interested in educational capability and perhaps increasingly so because the technology that we have brought to the world – communications and computer technology – has really changed the world scene.

We have brought three billion new capitalists into the world's free enterprise system in a very short period of time, in the last decade. Those people in India, China and other South East Asian countries, Russia and Eastern Europe and increasingly in the Middle East, all have access to knowledge, to communications capability and to computer technology. Those of us in countries like the UK and the US, who deal with knowledge-based economies to support our standard of living, our per capita income, recognise that we have to add value to the system to support that standard of living and, increasingly, there is competition for those jobs that add value into the system.

You can translate that into a smart engineer in China, India or Russia, who can contribute just as much as a smart engineer in the US or the UK at this point in time. There used to be a time, perhaps 10 years ago, when the country into which you were born really controlled your destiny, in terms of knowledge society and contribution and, unless you migrated from that one country to one of the few established economies, you probably could not contribute. That is no longer the case, however, and on a daily basis it becomes less and less the case, going forward. Thus, geographical location is no longer important and contributions come from everywhere. I will come back to that topic a little later in this presentation.

Engine of change – a technology-integrated life

Technology is the topic I would like to talk about. This slide shows five different examples of technology. Those of us in the audience with a little grey hair will recognise the beginning state and then the current state, and then you can project yourself 10 years hence into the future state.

Desktop computers were introduced only 25 years ago. They were hard-wired and they were stand-alone pieces of computer equipment. After a while, they became wired into local area networks and then into corporate networks and then into the worldwide web. Along the way, they became unwired, while they became connected to laptop computers, and today we have laptop computers which require no physical connection. We can have broadband wireless capability in the local area and tomorrow we will have broadband connectivity in the wide area. Increasingly, it is computation anywhere, any time, and it is increasingly more and more computer powered.

The telephone has changed dramatically and we really see this in emerging economies, where landlines are almost non-existent and everything is a cell phone. By the way, what is a cellphone? Today, a cellphone is a camera, it is a video display unit and it occasionally does voice transmission! It plays games and sends short messages that you can type with your thumbs if you are really clever, like any 14-year old.

TVs have changed, as have radios. The distribution of music has changed. We all know that there are more digital cameras produced each year than film cameras and, in fact, many of the film camera makers have gone to all digital cameras, and we all know that there are more digital cameras sold on cellphones than there are stand-alone digital cameras. These changes have taken place in the last two decades and you can only imagine the transitions that have occurred, and what will happen if we continue to bring more and more computer power, more and more memory density and more and more broadband wireless capability into these systems. We will see further transformations, going forward.

By the way, in case you did not recognise it on this slide, that is your national soccer team in all the images. It is important, when I give presentations in countries like Brazil, that I do that, and I suppose it is also important here in the UK.

Technology changes everything

The issue is that technology has changed just about every aspect of our lives: in the way we communicate; the way we access information; the way that we conduct business, and the way we entertain ourselves. The technology has become so fundamental to those four basic human functions that it is impossible to get away from it.

New fields Emerge

I would like to suggest to you that technology will continue to advance. I will do that by looking a little at silicon, but you cannot do that without talking about Moore’s Law. This is the law that Gordon Moore forecast in 1965, roughly 40 years ago. Gordon did not believe that the law would last much more than a few years when he forecast it and, in fact, when you read the original paper, you will see that he said that this could not continue. However, it has indeed continued for a period of about 40 years, and memory density and computer power doubles roughly every 18 to 24 months. It is quite amazing to have anything that doubles every two years for a period of 40 years but, when I suggest to you that this will continue for a further 15 or 20 years, you can imagine the continued capability that we are bringing forth.

On the left of the slide, there is a simple example of that. There is a cross-section, basically of a transmission electron microscope cross-section of a single transistor, built on a so-called 65 nanometer technology. You can actually see that the active gate is only about 35 nanometers across, but the printed dimension of the transistor is about 65 nanometers. This is then compared to an influenza virus. Those of you who are suffering from some form of virus might like to know what it looks like – and this is an image of one.

The real issue here is that the structures that we are making today are substantially smaller than viruses – they are roughly the same size as proteins which represent diseases. Later, I will talk a little about applications in the health sciences arena and how you can use structures similar to that on the left to help you to identify disease markers and diagnose diseases at very early stages. This is the state we are in today. Moore's law is 40 years old and going strong.

New fields emerge – extending Moore's Law

You can see instances of what it will look like in the future. The images in the upper left of this slide are in fact cross-sections of devices. We tend to have a new technology every two years and we are just coming off a 90 nanometer process and ramping 65 nanometers into volume production. In 2007, we will introduce a 45nm technology that shows a cross-section of a 45nm device. Just to show you that it is not just an isolated 45nm device, this happens to be the typical silicon wafer on which we manufacture our devices. [*Shows silicon wafer*] You can see that there are little squares on this wafer, each one of this is a static ram test pattern on 45nm. The test pattern has only 1 billion transistors in each one. I say only 1 billion transistors because there are fully functional static rams on this test pattern, which means today that we can manufacture 45nm devices and have 1 billion of them wired together and work. Ramping this into production, 12 to 18 months from today, should be relatively simple and straightforward.

At the same time, we also have 32nm transistors in our laboratory, and 22nm [*sic*] transistors in our laboratory, so the next several generations are already working in the laboratory and it is only a matter of $1 billion here or there to ramp them introduction, and a few billion dollars to build the factories to make that happen.

When you go beyond 15nm or so, or 10nm, you start to run into electrical challenges because you are scaling down devices to the atavistic level. There is the probability of impurity atoms being here, and leakage currents being higher than drive currents there. This can become a problem, so you have to start to move away from the standard CMOS transistor that we are showing in the upper left. I have just shown a few examples of things that might replace the basic electronic switch.

The basic electronic switch today is a CMOS transistor. It might be a tri-gate transistor, or it might be a nanotube, or it might be a quantum-well transistor, or a quantum dot. It might be all sorts of things, from research that is going on in our universities. The key point is that, whatever that switch looks like, it will probably not be much different than a CMOS transistor to make. The seven, eight, nine or 10 levels of metallisation that go on top of those switches to wire them all together to make functioning circuits will be pretty much the same as today. I am therefore fairly confident that the extrapolation of our current technology, plus these other technologies coming into play, will give us another 15 to 20 years of Moore's Law.

In simpler terms, for microprocessors such as we make today, they only have 2 billion transistors in them and there is a certain amount of functionality. You can imagine - looking 20 years hence, that there will be 10 doublings between now and then - the electronic functionality that you could see in about 2025. You could then start to imagine the sort of electronic functionality that you could see in the sort of devices that I showed on the earlier slide – whether they are telephones, TVs, radios or whatever they might be. We are talking about devices and you cannot even imagine what they look like today, much as you could not have imagined those devices 20 years ago.

New fields emerge – silicon photonics

Extending Moore's law is relatively simple and, along the way, there are some other interesting aspects. About a year ago, researches in one of our laboratories demonstrated things that people thought were very difficult, if not impossible, and that is continuous mode lasers with silicon. Why are those important? They are important because, as you have more and more transistors, more and more memory and more and more computer power, you need more and more data transmissibility or bandwidth, in order to keep up with the computer power and the high data densities. If you could do that optically rather than with wires – especially as you shrink wires down, you have RC time constants that go up and so you do not want the rate limiter to be data transmission, but you want the rate limiter to be how fast your transistors switch. Being able to put lasers on board the chip, or chip-to-chip communication, or system-to-system communication, greatly increases the throughput and the performance. Silicon photonics will be a big part of this and it will just complement Moore's Law from the transistor density, going forward.

When I tell people this, they always ask the same question that Gordon Moore was asked, the day that I joined Intel 32 years ago. Gordon said at that time that Moore's Law was Moore's Law, and that he could see it going on for a few more years. Someone raised their hand and asked, 'Yes, but what will you use all those transistors for? Do we not have enough already?'

I remember dealing with Ford Motor Company in 1980 in the first years of electronic engine control. The memory for the electronic engine control module was 32kbits, and people said that was all they needed to do electronic engine control. Today, however, you are talking basically about gigabits of capability to do the same function with cascation today. When personal computers were first introduced, the 80/80 was basically a few thousand transistors. Today, a run of the mill microprocessor has perhaps a few hundred million transistors in it and at the highest end it has about 2 billion transistors in it. People like Lord Browne in the petrochemical industry want more and more computer power. If you talk to people who are doing digital content creation, they want more and more computer capability. If you talk to the financial industry, they want more computer capability. I see that there is no stopping the demand or satisfying the desire for more and more computer memory capability, going forward.

New fields emerge – user aware computing

If you look at some of the interesting aspects of what you can do with these added computer capabilities, you start to see that computers can begin to act as more than stand-alone computational elements. By 'stand-alone computational element', I mean that you put some data in and the computer does something, and then spits the answer back at you. What you would really like would be for computers to be self-aware, or user-aware. 'I am a user and my likes and dislikes for information are such. Computer, when I log on, please recognise that and go out and collect that information and bring it back to me. And, by the way, please learn as we go along what my likes and dislikes are, so that you can further refine that.' Let us do intelligent searches, or let us do adaptive recognition of the environment and then give a response in accordance with that.

New fields emerge – DARPA Grand Challenge

There are many exciting things going on in this field, and I would like to show you just one. This is the example of DARPA, the Advanced Research Projects Agency in the Department of Defence. Approximately two years ago, they said they were very interested in computer applications in military environments – they are an agency in the Department of

Defence. Doing such things as flying aeroplanes and drones under computer control is rather straightforward because, when you are flying into the sky, there are not many things to run into. You do not have to navigate along a road or do anything like that, and so these have become commonplace elements in the military community.

What has not become commonplace is adaptive computing for automobiles. DARPA therefore set up a challenge to have a car that could drive a route of about 200 kilometres, from the outskirts of Los Angeles to the outskirts of Las Vegas, Nevada. This went through dry lake beds, over trails, cross-country on roads, and they had to do this without human intervention. All the DARPA would do for the contestants was in fact give them a few hundred GPS co-ordinates two hours before the event started and then the car had to self-navigate the rest of the way. They had to determine such things as whether there was a boulder in the middle of the road or a sage brush – something it could run over. It would obviously lose GPS contact if it went through a tunnel, so that had to be dealt with.

We ran the first element of that about 18 months ago. We put a $1 million prize up to get people interested and there were some 20 entrants. The entrant that went furthest at that time was from Carnegie-Mellon University, with a Hummer, powered fortunately with a great deal of Intel hardware. This went a total of 10 kilometres before it ran off the road: the tyres kept spinning and, when the tyres caught fire, the judges declared that it was over. The Hummer entered this second round which took place a few months ago, and that is the car that is in the back [*on slide*] with all of the hardware on top.

The interesting point is that, in the space of one year, not one car finished the first round; in the second round, five cars finished the entire 200km and the winning car happened to be from a small university in Northern California called Stanford. [*Laughter*] Being a graduate of the engineering school, I am a little proud of that. This was also powered with Intel hardware.

I will show you a short video of that. The video is in two parts, first with some manned test runs with the vehicle and then, in the second part, there are the actual races, showing the vehicle on the race course.

[*Video Shown*]

"Stanley" is the name of the vehicle, and the part of the video that I find most interesting was the need to clean the windscreen off when there was no one sitting in the car! [*Laughter*] I presume that there were some sensors behind the windscreen that required that. Nevertheless, this was quite an accomplishment in an 18-month period and one can only imagine that, as there is increasing computer capability going forward, and compacted in a small area, there are some exciting things that can be done.

It is still true that, even though our most powerful microprocessor has the essential capabilities to respond to external stimuli, equivalent to that of a cockroach perhaps, the human being is a very adaptable computer in terms of external recognition and response. It takes a great deal of computer power to try to emulate that capability. However, as we have more and more computer capability, we come closer and closer to that in this area of proactive computing. We all know how effective computers are in terms of predetermined scenarios, such as playing chess or something like that, where there is only a finite number of moves that you can make. It is pretty clear now that computers can do a very good job against the best human chess players in the world. The challenge here is to expand beyond that to where there are totally unforeseen circumstances, and the immense amount of compute and recognition capability required.

New fields emerge – dynamic physical rendering

There are other interesting aspects coming along and I wanted to show you one that is very far out, relative to the one we have just seen. We should recognise that the one we have just seen was effectively impossible two years ago, and then it happened.

This is something called dynamic physical rendering. If you look at this rendering of an elephant, each one of those little red balls really represents a physical entity which, under software control, could assume its position to create that three-dimensional figure of the elephant. This is referred to as claytronics and there is work going on with Carnegie-Mellon and some of the Intel people, concerning how to do a dynamic, three-dimensional representation of complex images – not a rendering, but a physical 3D image of these, such that you can examine them.

How can you do this with sufficient resolution to make it useful? I will show you that this is at a very early stage and the little building blocks here are very large today. However, you can imagine that with the continued borrowing of Moore's Law for a further 10 years or so, we might actually get to this case.

New fields emerge – traditional 3D

What are we talking about here? We are talking about such tasks as, if you are into the medical visualisation characterisation where you view images of the human body as slices, then it is possible today to use software to build those slices back up into a three-dimensional image. You render that as an image and then rotate it as an image – you can do all sorts of clever things. However, what if we could build that image into something real in front of us, and almost have it in our hands, turn it over, and look at it? That is what we are really striving to do.

New fields emerge – catoms

The way we would do that, simply, would be if we had cameras to catch a 3D image of the physician, and then build that image of the physician through claytronics, or catoms. Each one of those elements really has a number of interesting characteristics. They are self-configuring, relative to each other, so they may be surrounded by electromagnetic coils, such that they can move relative to one another. They can have visualisation elements associated with colour and texture associated with them, but they can be controlled by some external software programme telling them how to align. Supposing that we had billions of those at a very small level, we could build up very complex images.

New fields emerge – catom prototype hardware

This sounds far out and it sounds like science fiction today, but let us take a look at the prototypes. These are two-dimensional prototypes because we are not even through to the three-dimensional stages, and this is what they look like relative to a Coca-Cola can, as shown on the left of this slide. You can see the little electromagnets built up around the outside, such that they can configure in the two-dimensional image. We need to shrink these down to such a size where we can have decent resolution and texture for a 3D image. This requires an immense amount of computer power and an immense amount of concentrated electronics, and computation capability. This is something, however, which can happen in the next decade or so, going forward. This is a very interesting application and capability.

New fields emerge – technology in healthcare

There are other exciting areas, too. One is healthcare. Healthcare is an issue of great similarity between the United States and the United Kingdom. We are further ahead of you in one respect, in that it eats up a bigger part of our gross domestic product than it does of yours. The challenge, in both countries, is really a standard business challenge.

If you look at healthcare, there is a distribution of costs associated with it. If you do a standard Pareto analysis, an 80/20 measure, then 80 per cent of the healthcare costs are sustained by 15 to 20 per cent of the population – that 15 to 20 per cent of the population who are chronically ill or very old and, usually, if they are very old, they are chronically ill. Unless you can impact the healthcare delivery cost to those chronically ill people you cannot begin to touch the overall healthcare cost problem. I call it a problem because it is impossible to have your healthcare costs escalate much beyond what we have in the United States. You can already see that it is almost impossible for companies in the United States, like General Motors and Ford, our steel companies and our airline industries, who have pensioners and employees, to compete with the current healthcare costs. We are running 16 to 17 per cent of gross domestic product, while here in the UK it may be barely a double digit number at nine or 10 per cent. This cannot continue to outrun inflation, as it is on both sides of the ocean, and so we will have to do something about it.

The only way that I know how to do something about it is in fact through information technology. Although the healthcare industry has wonderfully complex pieces of equipment, CAT scans, MRIs and so on, it is not an integrated system and it is not proactive in its monitoring of people. It is a mainframe computer system. In the healthcare industry, a mainframe is the hospital and it has not really adapted to a diversified computer system – which is the equivalent PC that allows the patient to stay at home and allows their conditions to be monitored at home. It minimises trips to the emergency room, and also trips to the hospital. There is thus immense interest on both sides.

Your National Health Service is making massive investments in information technology and there are equivalent investments in some of the vertically oriented health delivery systems in the United States, such as the Veterans Administration, Kaiser Permanente and Sutter and others. They have to employ information technology in a major way to go forward and this has to focus on the people who have chronic illnesses and, in fact, people who are older.

I wanted to show you a quick video from an organisation that is promoting the use of technology to monitor people at home, just to show you what can be done.

[*Video Shown*]

There is one thing that is eminently predictable, and that is how many people in the US and the UK will become elder citizens in the next few years. This is effectively a tsunami that you can predict. We are all facing that and it is impossible to maintain our current healthcare systems with an under-investment in information technology.

A very simple way to think about this is through the amount of technology that you can put in someone's home today, using standard off-the-shelf technology, for the cost of one night's hospital stay. It is an incredible amount of technology that you can put in and, if you can remotely determine whether it is a diabetic or cardiac problem, or asthma – whatever the chronic illness is – if you can detect when people are starting to drift into a poor situation which might require hospitalisation and catch that beforehand, you could take an immense cost out of the system. We will have to see that on both sides of the ocean, if we are to have vibrant economies going forward.

New fields emerge – single molecule detection

There are some other exciting things you can do, too, and that is in the area of single molecule detection. I mentioned earlier that the size of structures we make in our devices are, in fact, the same size as viruses and proteins. If you start to say that the treatment of disease, by and large, is detection and then treatment, then the earlier you can detect a disease, generally the higher the probability of the success of the treatment. If you can determine what the disease marker is, or the form of protein or whatever that might be, and then detect that very early on, then you can respond to diseases before they become troublesome. This is one of the things we have been doing, and it is taking the structures that we produce and using those effectively to concentrate or attract specific organic molecules – proteins, which might be disease markers – and then use some Raman spectroscopy to identify single molecules. Think of that as a single molecule disease marker, at very early stage.

Substrate looks something like that on the left [*on slide*]. There is a DNA particle on it but the interesting things are the 10 nanometer gold particles on there, which actually act as attractors or concentrations to the disease markers that you are trying to look at. Then, in fact, the signal on the right is just a spectrometer of the presence of one molecule, or the absence of it.

If you can tune this to look for specific disease markers – cancers and what have you – then we can do a much better job of early detection and treatment. There is some very interesting work going on, with people like the Fred Hutchinson Cancer Research Center and other cancer centres in the US, with our researchers, looking at things of this type. I have great hopes that we will be successful in doing some of these things but I just hope it does not add more cost into the system. Quite often, that is what happens when we have new medical procedures – all we do is increase the total cost associated with treatment, as opposed to saving money, but I hope this will reverse that trend.

New fields emerge – connecting the digital world

I wanted to move from some of the excitement in computing to perhaps the excitement in the area of broadband and broadband wireless capability. The United States has been lagging in wireless capability compared to Western Europe but there is exciting new technology coming out, which has the possibility to impact both sides of the ocean and basically every country in the world, and that is something called WiMAX technology.

Most of you are familiar with WiFi, which is a short-range broadband technology with about a 90m reach. WiMAX is a broadband, large area technology, which has a reach of about 50km. As the whole world is basically moving to wireless conductivity, and the devices we have are going to wireless conductivity, having broadband reach is incredibly important. I therefore wanted to show you a little example with an animation of the Academy's lecture theatre and the surrounding London environment, and show you the reach of this technology and what it can do.

[*Animation Shown*]

This is from a company called skylinesoft.com, which does these types of images. We are zooming in over the Thames and past a few of your landmarks, and coming to the Royal Society. The green circle there shows a WiFi capability, and if we had broadband wireless here – I do not know whether the Academy has that, but it certainly should, that would be the reach. However, that reach is rather limited and, if you really wanted to extend that capability, WiMAX has its so-called 802.16, and there are various varieties of that, which would have that sort of reach, point to point. This is a multi-megabit per second type of broadband capability – the type of thing that you would like to have if you were connected to the internet, or to your virtual private network for your company or what-have-you.

This offers huge opportunities, not so much for cities where there is already a strong infrastructure. For example, if you went to Tokyo – and Tokyo has almost fibre to the home and DSL capability that is able to communicate at 30 megabit/sec capability and is very inexpensive – then WiMAX does not add much to that, other than mobility. However, if you started to look at rural areas, or developing countries who do not have a wired infrastructure, then this is a very inexpensive proposition. I think we will see the same uptake of this technology as we saw of wireless telephony in the first place in these economies. In fact, you cannot go to an emerging economy anywhere in the world where wireless telephones do not outnumber wired telephones. This will be the broadband wireless capability.

There are essentially over 100 trials taking place already around the world – commercial trials, with immediate implementation. The next generation of laptop PCs will come out with, probably, add-in cards which have a WiFi capability, a WiMAX capability, and hopefully also a 3G capability. Making it simple to use, the computer will sit down in the presence of a wireless signal, determine the best conductivity to that wireless signal, and connect you without you having to do anything, to the best protocol that is available. This is more like anytime, any place computing, on a broadband scale, and you can start to see the services, capability and convenience that this will bring to the consumer, going forward. I would like to suggest to you that technology will continue to advance.

Opportunities constantly evolve

The key point I am trying to make with all of this is that technology is not slowing down. Moore’s Law will continue to go, and it will go on an exponential basis, so you can expect everything else to follow along on an exponential basis. There will be new capabilities and new applications of technology around this. The base technology is basically a tool and we keep applying this tool to different problems, and bringing wonderful results. The best part is that the tool becomes twice as powerful every two years, which is very nice.

Designing your future

If you step back from this for a moment, there are about 1 billion people in the world today who use this technology and they are internet-savvy, but where will the next billion or 2 billion users come from? There are some very interesting answers. In the UK, for example, you happen to have an elderly population, and many of us in this room are members of that, so we can speak authoritatively on this topic. You have an elderly population, however, which is under-represented amongst internet users, especially compared to the United States. You have a much lower fraction people over the age of 50 who are internet users than in the US.

There are three reasons why you should be concerned about that. The first is that they will probably not be terribly productive members of your economic structure, because just about any job in a knowledge-based economy will require some computer skills. Secondly, as your government goes digital and provides services and healthcare which require digital inclusion - and the patient has to be computer literate to take advantage of that - they will not participate there. Thirdly, just from a societal aspect, as the world goes digital, you have to go digital to be included in the world – and that includes music, entertainment, communication with your friends, information access. If all the cameras in the world are digital cameras and you do not know how to run a computer, you will not see a lot of images. If all the videos in the world are digital, you will not see many of those. There are therefore reasons to try to include all sorts of people, all members of your society, and make them computer and internet literate.

Then, there are also entire societies that are not computer literate. If you go to sub-Saharan Africa, you basically do not find computer users. If you go to those parts of the world, you find that there are four critical things on which you need to focus:

- You need affordable hardware – computers are becoming cheaper every day, now costing in the range of a few hundred dollars.
- You need connectivity and, strangely enough, connectivity is often more expensive than the computer in these countries, because you still have nationalised telecommunications systems who use it as a revenue source as opposed to a service to their systems.

- You need rich local content because, if you are in Chad or Nigeria, you do not necessarily want content that is appropriate for London, Westminster or San Francisco, but you want local content.
- You need teachers who are literature, to be able to teach the young or the older people how to use the technology.

There is thus plenty of opportunity here to have the technology not only grow in capability, but also to grow in usage patterns around the world, if we address these four issues that I have must mentioned. That is rather what this business is …. [*Tape change: no overlap*]

Designing your future: education leads the way

[Some of the most important aspects … innovation] ….. our economy, and we always come down to these same fundamental issues. There are three things that are terribly important: education, ideas and an environment for investment and innovation, or an environment to create new businesses and new products. The United States and the UK have many similarities facing them in these three fundamental areas.

For example, we have about the best universities in the world between the two of us but, increasingly, we are using our universities to educate foreign nationals, which is a very interesting proposition. Increasingly, these people are going back to their home countries to make use of that education and, increasingly, the universities in their home countries are copying what they see at Oxford, Cambridge, MIT or Stanford. We were chatting about this just before this presentation and saying that, increasingly, universities like Stanford, MIT and Harvard are going to help the Chinese – or the Indians or the Malaysians or the Russians and so on - to make their universities the equivalent of ours.

Education is critically important, and especially education in what I would call maths, engineering and the physical sciences. This is not just to appreciate what we are talking about in the way of technology, and using that technology effectively, but also to make rational decisions about some of the problems the world faces – whether that is global warming, energy conservation or whatever. If you depend on the news media to provide you with statistically significant conclusions about things, I would like to talk to you afterwards! [*Laughter*] An informed electorate, and someone who understand the basis of statistically significant trends and things like that, is very important to either of our countries – or the countries of any of you who are citizens of other countries than the two I am talking about.

So building schools programmes to train teachers, and treating teachers as professionals and giving them ongoing professional upgrade, is extremely important. It is incumbent upon countries with very advanced economies to recognise that the only way to continue to support that standard of living is to add more value than your competitors – and the only way to do that is with an educated workforce.

Designing your future: research and development

R&D is absolutely critical because that is where the new ideas for products and services come from. Research and Development comes in two flavours – that invested by the government, which usually then takes place in the research universities, and that invested by business and business concerns. Businesses are usually associated with short-term research and development or product development and not so much the basic and long-term R&D. Universities have the domain of the basic research and development, which might not be commercialised for 10 years or so. The investment in research and development at a given fraction of your gross domestic product is terribly important and this is one of the things we have been trying to convince the US government to focus on in terms of *our* future as a competitive society. There are many positive aspects of the things that the UK is doing in this area but both of our countries have a challenge from the rest of the world in terms of our leadership in this space, going forward.

Designing your future: create the environment

Lastly, there is the creation of the environment. The environment is something that governments quite often control through their tax and other policies. It is relatively difficult for me to see, if the United States really does not want to allow stem cell research from government-funded resources, how the United States will be a leader in that field in the future, and that is an environmental factor.

If you have very high corporate tax rates which inhibit the investment in innovation in your host country, then that investment will probably go to some other country. We have seen that migration of investment to Eastern Europe and the migration of investment to Asia, where low tax rates are a fact of life. It is all around us – in fact, we do not have to go that far, but you can just go to Ireland with their 12% corporate tax rate and do a net present value difference from a facility that we might create and it is over $1 billion net present value difference just if the corporate tax rate is 12% compared to 35%. I have a difficult time convincing our shareholders that I should give the government $1 billion rather than giving it to our shareholders, so guess where the investment goes. It is that type of environment that governments can create through their policies - their spectrum policies, their incentive policies, their legislative policies, their patent policies and so on.

Inspire innovation

The key point is to inspire innovation. We all have to focus on the three key elements of smart people, which is the education system; smart ideas, which is research and development; and then the environment that allows smart people to work with smart ideas and create wonderful new products, companies, services and so on.

The only limitation I see in this whole area is that which we, as citizens, tend to impose upon ourselves through our government actions. This is why you see the debate in the United States about the competitiveness of our economy, going forward, and why you see the academicians and business people all raising their voices in unison and saying that, to be a competitive society, we have to make massive changes in the way we do our elementary education, the way we invest in research and development, and then the environment in which these exist.

Competitive success

For the last few moments I would like to shift gear and give you the benefit of my observation over the last 32 years in the semiconductor business, watching the computer business growing during that time. I will give you perhaps three observations about what is important.

Nothing beats investing in good people and ideas

The first is relatively simple, and it is that nothing beats investing in good people and good ideas. I always like to go back to the original Intel business plan, which was 157 words, type-written. It had three spelling errors and several grammatical errors. It was obviously put together before spell check, or before the personal computer. Effectively, the business plan said, 'We think there is a new technology which is just coming into the market, called integrated circuits, and we think there is an opportunity to build a business around this.' Even though our first products were in fact memory devices, those were not the first things the company tried to create from integrated circuits, which is interesting.

The money that came into the company, starting with venture capital funds, was invested in the quality of the people. Arthur Rock is 'Mr Venture Capital', who started the venture capital industry in the United States and was on the Intel board until recently. If you ask Arthur why he raised money to invest in Intel, he says that he had confidence in Bob Noyce and Gordon Moore: good people, with good general ideas - recognising that the environment would change and the ideas might lead in different directions but that good people would be able to follow that.

[*Slide*]

We have tried to continue that and we have tried to employ the best talent we can find, wherever it resides in the world. I wanted to give you a brief glimpse inside Intel, showing some of our people – what they do, and what they think about the work they have in front of them. This video shows the kind of culture that we have tried to create in the country. It was taken in our manufacturing facility in Albuquerque, New Mexico. You will recognise this as one of those multi-billion dollar wafer fabrications that makes these 12" diameter wafers I showed you earlier. Let us look at what they have to say about their jobs.

[*Video Shown*]

As I have said a few times, you have to hire a bunch of smart people and give them a few billion dollars, and you achieve great results.

Market share is gained and lost during transitions

The second point I wanted to make is that market shares tend to be gained and lost during transitions, and especially during technology transitions. If you look at the history of our field, the first electronic switch was effectively a vacuum tube but no vacuum tube manufacturer made it into manufacturing integrated circuits – so there was a technology transition and market shares were totally lost associated with that transition from the original switch manufacturers.

The question that we tend to face in our industry today is that, when the next electronic switch comes along, who will make the transition – who will maintain market share and who will lose it? There are a great many other examples around the world. There is Nokia, which made the transition to digital wireless capability ahead of Motorola and gained a tremendous amount of market share and went into a fairly dominant position in handheld wireless communication.

IBM made the transition from mainframes to personal computers, interestingly enough, and then had a very strong market position initially but then lost that market position over a period of years through the transition of distribution channels for the technology and how they deliver the technology to the customer. Eventually, they went out of that business, selling their capability to Lenova. Whenever there is a transition, therefore, whether it is a technology transition or a market place transition, this is the time when market shares are won and lost and that is when people need to be especially paranoid, going forward.

Change before you have to

The last piece of advice in this general area, which serves our industry reasonably well, is that you need to change before you have to. There are many examples of industries, or segments of the industry, that do not change until they are forced to do so by competition, or forced to by their customers.

The music industry comes to mind as one of the most dramatic in this area because it has been subject to constant technology changes over the years – from records, to tapes, to CDs, to distribution over the internet. Each time a transition occurred, they in fact resisted that transition until it was forced on them by their customer base. They were able to maintain that, because they controlled the source of content through the first transitions and each time they actually made the transition, their revenue grew because of it – because of the increased fidelity and increased capability.

However, with peer-to-peer file-sharing technology, the music industry resisted the distribution channel of the internet to deliver music to their customers and almost lost the entirety of the business. In fact, today, you can still – if you are so inclined – go and download just about any piece of music illegally on the internet. I usually like to ask audiences of this type, how many of you have downloaded music illegally off the internet? [*Show of hands: laughter*] You see, there are a few of us who are willing to be honest about this. However, if you ask that of your children and grandchildren, I think you will find almost 100 per cent of people raising their hands, and that is an instance of where the industry did not change and accommodate the technology. Steve Jobs with iTunes and a few other applications are now making viable commercial models available but this is very slow.

[*Photo – fortune cookie*]

I will leave you with my last piece of advice. This is the best piece of advice I have ever received regarding competitiveness around the world. This is true. I was sitting by myself having dinner at Chef Chu's in Silicon Valley – my favourite Chinese restaurant. I had my shredded chicken salad, followed by lemon flavoured chicken and whatever it was. When my fortune cookie came, I opened it and it said: 'The world is always ready to receive talent with open arms'. I thought about that for a minute – this was just at the time when outsourcing and offshoring was becoming a popular topic in the United States. It was when these 3 billion new capitalists in Russia, Eastern Europe, China and India had joined the world's free economic system. I thought to myself, that is very true: no matter where that talent is, the world will chase after it.

This is what I would like to leave you with today. This is a statement of the competitiveness in the world today, and who the winners and losers will be. The winners will be the people who create the talent and are able to hold onto it. If you do not like my fortune cookie, I invite you to go to your own Chinese restaurant of your choice, and see whether you can find a better predictor of the future.

Thank you very much for your attention. [*Applause*]

Questions & Answers

Lord Broers: Thank you for that brilliant lecture, which was so broad-ranging and thought-provoking. We all accept – and particularly we engineers – that technologies always change the way that humans live but, in this day and age, it is doing that more and more quickly and it is accelerating in pace. From companies like Intel, I am very pleased to see that your viewpoint is a broad-ranging and serious philosophical look at what you are doing to the world. The world is changing very rapidly and the opportunities are huge, but there is potential for damage and for leaving people behind. You have covered all those topics very eloquently and it has been a fascinating lecture – we have gone all the way from advances in medicine to social responsibilities around the world, and the excitement of where technology can take us, so thank you for a brilliant lecture.

Dr Barrett has offered to answer questions and so it is now your turn.

Dr Eric Duckworth, OBE FREng (Comino Foundation): That was a fascinating talk. The car chase video was very impressive, because we have ladies here who can steer cars while powdering their noses!

There was an aspect which I thought you have not exhibited, Dr Barrett. As the devices become smaller and more powerful, they use less material and less energy. They enable people to communicate more without having to make physical journeys and this has a great effect on carbon dioxide emissions, because they use less material and less energy, and fewer resources. The more we persuade people to change from buying large consumer goods to enjoying themselves more with these devices, the more this will help to reduce carbon dioxide.

Dr Barrett: Yes, that is a valid point. I would only add that the technology is certainly capable of making standard consumer goods more efficient as well. Automobile emission controls today would not be possible with mechanically-based systems and you really need electronics to do that. You really just need to run down the list of energy-consuming devices and you can make them more efficient and more effective. We have done some very interesting work with British Petroleum in terms of remote sensors and anticipating maintenance in very hostile environments. There is a whole variety of ways that you can use the technology to increase energy efficiency and offset any negative impacts on the environment. That is very true.

Dr Nigel Horne, FREng (Aspex Semiconductor Ltd): I want to go back to the technology you mentioned, which has obviously driven Intel over the years. You mentioned Moore's Law, which you have shown will continue for a further 15 or perhaps 20 years, by a reduction in the feature size. Your company is shipping semiconductors now with multiple processors on them so that not only do you have the feature size advantage, but also the parallel processing as well.

I have two related questions. First, how far do you think this will go? Two, four, eight, 16, 32, two million – what? That is, of course, with standard processor architecture.

The second and related question is, how far will this drive a rethink away from the von Neumann architecture, to achieve the advantage of having Moore's Law?

Dr Barrett: Obviously, one of the drives to multiple compute cores is driven from the fact that we can no longer afford the energy budget that goes with just a single-threaded device and just running transistors faster and faster. There is the advantage of Moore's Law in that, by having more transistors, you can scale back from the speed at which you are switching them. You can still achieve energy savings and you can use the multiple core architecture to obtain improved performance.

We are doing our Developers' Forum in San Francisco as we speak, and we have demonstrated our first four-core processor. Basically, that is a four physical core – and each one of those cores is multi-threaded and so, effectively, there are eight cores in that system. That is a product for next year. Every product we have is in fact building on that capability. There are some immediate applications that are very well-suited to that, with the parallel processing issue and the image issues. Video and the gamers will love that – anybody who is doing that kind of digital content creation will love it.

Quite frankly, it will require a total rethink of the entire software infrastructure to take continued advantage of this, going forward. It would be very simple if we just continued with single-threaded applications and could just crank up the transistor speed but that is no longer physically possible. You therefore have to rethink the entire compute architecture and software architecture to achieve maximum benefit.

I cannot answer your question as to exactly how many there will be but, when you stopped at 32, you did not have enough. A million might have been more than enough – but somewhere in that range.

Mr John Lowe (The Smallpeice Trust): I am impressed by your obvious care about people and, in particular, young people in education and I know that you do a great deal at Intel. From your experience, what do you recommend that we should do on both sides of the Atlantic, perhaps with Government, or perhaps with institutions as represented here, to increase the *effectiveness* – not the number but the *effectiveness* – of the efforts that we are making to get young people to take up technology, science or engineering careers?

Dr Barrett: Thank you. I can speak most knowledgeably about the United States system, although I do not think the UK system is substantially different. The biggest challenge facing us in the United States is two-fold. First, we do not have the qualified teacher core in place to enthuse young people to be interested in maths and science. It basically takes a very highly qualified professional group of teachers, all the way through the [??K through] 12 curriculum in the first 12 years or so, in the educational process, to get children interested in maths and science, and to appreciate the capability. Effectively, all it takes is one bad mathematics or science teacher to turn a child off.

In the United States, each time you go in front of a maths teacher, you only have about a two-thirds chance that they are accredited, and one-third of the time you will be faced with a non-qualified or non-accredited teacher in that space. You do not need a mathematics degree to figure out the probability of having 12 qualified teachers in a row, if there is only a two-thirds probability each time. We do a very effective job of weeding them out, and we need to do a much better job at that.

The second aspect is that we also make a fundamental error in trying to drive all children at the same speed through the same subject matter. The way we are addressing that in the United States is with a greater focus on what we call 'advanced placement courses'. This involves moving children who have greater capability faster, and getting them to do the college-level courses while they are still in high-school. It is a matter of not letting the lowest common denominator drive the speed at which the process occurs, but to let people move at their own speed.

Aaron Ezgar (London Business School): What is the hardest part of running one of the world's largest and most dynamic companies? And how do you manage that?

Dr Barrett: Fortunately, I graduated to Chairman about six months ago and I have someone else managing the company – and I manage him, with the rest of the board! [*Laughter*] It has become much easier for me in the last six months.

From my personal perspective, I love the technology and I loved coming to work every day, so it was not hard to be involved in technology and the management of the company on a daily basis. Perhaps the most difficult part was being involved in making decisions about what to do next in the way of architecture, product or something else.

Let me give you a very simple explanation of why I thought that was difficult. Our product turnover is almost 100 per cent each year. This means that, by December of each year compared to January of that year, about 90 per cent of the revenue comes from products that were not there in January. If you guess wrong, it really hurts. That was probably the most difficult part of the task, which was to anticipate where the environment would go and what the products needed to be to fit into that. By environment I mean the products, the software and the applications that the market would want. The other part of that challenge is that none of these products have a one-year development cycle but they usually have multi-year development cycles, so that you are always reaping the benefits of decisions you made two or three years ago, which can also be a challenge. That was the most difficult part.

From a technology and manufacturing standpoint, if you love the technology, then you have to enjoy every day that you go to work – and I did.

Lord Broers: But that problem has accelerated, has it not? There were happy days in the seventies, when the generation of microprocessors would last a few years.

Dr Barrett: Yes. Everything has speeded up. Some people like to describe the technology and product architecture as becoming more complex but, several years ago, we decided to outlaw the word 'complexity' because it was becoming an excuse for why you could not go faster. We therefore legislated that you could not use the word 'complexity' in any presentation at Intel as an excuse as to why you could not go faster. It was not just because we took that one step, but we were able to take the process technology, which was originally on a three-year timetable and move it to a two-year timetable. Even though some of our competitors complained about that, we thought it was the right thing to do.

Lord Broers: But, in effect, there must be a sound barrier there somewhere. If you go too fast, you will never get back those billions you were talking about?

Dr Barrett: Yes, there is precisely that, because the capital expenditure that is needed for each one of these new technology – all of the equipment comes from a wide variety of vendors. If you get too far ahead of them, then you have to pay astronomical sums to help finance their part of the operation. You are then paving the way for the entire industry. We try to operate perhaps six to 12 months ahead of the competition, and that is a tolerable tax that you must pay from a leadership standpoint. Fortunately, size and scale allow you to pay that tax back rather quickly.

Lord Broers: And you have never persuaded the competition to slow down.

Professor Patrick McKeown, OBE FREng (Cranfield University): This may sound a little naïve to many people here, but you spoke about photonics on the chip, which is fascinating, and lasers on the chip and so on. Of course, it is possible to store information electromagnetically with electrons, but is there a good prospect of storing information photonically?

Dr Barrett: I guess, perhaps. As I tried to articulate, our challenge is obviously the data transmission rates from memory to processor, or from element of processor to the other element of the chip. Frankly, as we become more sophisticated and can make bigger and bigger chips and smaller and smaller lines, that is where the whole RC time constant becomes involved, and that is why you want that capability.

We have not been moving in that direction but we have been moving just in the data transmissions space. By the way, that is still many years off with the silicon photonics that I was talking about.

Lord Broers: Are you trying to invent the nano-photon storage ring? This thing does not exist.

Ms Rachel Arning (Pritchard Englefield): You mentioned that there is quite a direct link between investment and research and development projects. I saw in your slides that you are predicting that in the future you will be able to develop smaller and smaller particles on silicon. However, there will come a point when that will no longer be possible and then you will have several question marks – such as perhaps using carbon as a material to continue. However, if you cannot find something to replace silicon, how do you think that will affect the global economy generally?

Dr Barrett: That is an excellent question. I should preface my response with the fact that the cliff that we all look at, when silicon no longer works, or when we can no longer scale the transistor, has always been 10 to 15 years out. It was 10 to 15 years out when I joined Intel 32 years ago, and it is still 10 to 15 years out. That is to the credit of the wonderfully talented engineers that we have hired and to their ability to do such things as routinely print billions of images substantially smaller than the wavelength of the radiation they are using to print those images. There are things of that sort. They create layers of dielectrics and other layers which are controlled to plus or minus one atom over the entire size of that 300mm diameter wafer. These are very sophisticated manufacturing techniques. I am therefore looking at 15 years of lifetime ahead of us, for the next 15 years.

Ms Rachel Arning: [*Without microphone*] So you are not looking at other changes beyond that?

Dr Barrett: The major change will be the switch that replaces the CMOS transistor. Those are the question marks I had up there. I can see another 10 years of the CMOS transistor being active and I could even extend it beyond that, because we are still doing basically two-dimensional structures, and we could go to three-dimensional structures to scale out vertically as well, to scale more capability.

In terms of just shrinking lateral dimensions, I can see another 10 years and the smart engineers will probably extend it beyond that. Eventually, however, it will be a quantum dot or some other type of switch that allows you to continue to scale down. If you can go to a single electron spin, being the information, the ?one or zero, then you get down to the absolute atomic level before you finish the scale.

What happens after that is open for investigation in our research universities and that is why the R&D investment is so important. No one has picked what the next switch will be, beyond the CMOS transistor. The alternatives I have shown are just *some* of the alternatives. Perhaps one of those will win, or perhaps it will be something else, but that is the absolute importance of continuing to invest in basic research. That is the research that is 10 or 15 years from commercialisation.

I would like to think that far ahead but frankly, when my revenue turns over every 12 months, then thinking 15 years ahead is a challenge.

Professor Julian Hunt (University College): It sounded as though you felt that people had to adapt to technology, rather than technology adapting to people. Some people have asked, when will we have a computer that talks to us, whereas you have said that older people are not adapting fast enough to the computer. Is that not the wrong way round?

Dr Barrett: Ultimately, you need to address problems with solutions. There are many problems out there. Visually impaired people are a challenge and there is reasonably good voice recognition data and speech-to-text/text-to-speech capability. I was at a computer centre in Lima, Peru, about a year ago, which had been started by four visually impaired or blind university students who were all active computer users and active internet surfers. This was all basically text-to-speech translation to them. By the way, they not only had a computer club but they created a business, because they felt that they could answer people's questions easily over the telephone about what was wrong with the software and so on, without seeing what was on the screen – because they could not see what was on the screen anyway. They had a very active software consultation business there.

The comment I made about senior citizens in the UK had two aspects to it. First, the industry has not made a serious effort to accommodate older people but it has really focused on the early adopters and the younger users. It has been the generation that has gone through school with computers who are the heavy users. The industry has more recently started to look at the next billion users and that would include the elderly, or the people who are not early adopters. You will probably see a combination of things coming from that, including how to market the technology and how to train people to use it. I am quite sure that people who are 65 years of age would rather be trained in the technology by a peer in their age group than a 19 year old whiz-kid. They would rather have someone who can sense the same trepidation, fear, uncertainty and doubt that they have about the technology. The system has not accommodated that.

We really have not been serious about sending ethnographers to watch elderly people use the technology, to see how you might accommodate the hardware and software to their usage patterns either. All of those are things that are just starting to happen now, but they all basically relate to using technology not for technology's sake, but using technology to solve a problem. That is where the industry has been going: it is the solution that matters, not the technology. Who cares whether our technology has 1.9 billion transistors or 2 billion transistors, and whether it runs at 4 gigahertz or 3.6 gigahertz any more? None of you care about that, but you care about what the technology does for you. If the technology helps seniors to communicate; get services from the government; facilitate their medical care, and shop on line, then those are the issues that will attract them to use the technology. We really have to do a better job of adapting the technology to the use patterns and the solutions that people are looking for.

?Peter Park (London Business School): My question is about your recent chapter to the *New Trend*. Recently, Intel launched a new law, and also you released a new product category 5. Which external factor made you submit this chapter and, secondly, when was Intel's management aware of this external factor?

Dr Barrett: The answer would be a follow-on to the previous question. If you start to deliver solutions to the market, rather than technology to the market, then you realise that platforms or integrated solutions are important.

The first solution we delivered to the market was a laptop wireless capability – the Centrino product line. That technology was introduced to the market several years ago. It was a solution for the mobile market place and you have seen the follow-on, which is a solution 5, for the entertainment PC or the living room market place. The next platform or solution that you will see will be a remake of the computer for the enterprise or business market place.

Starting several years ago, we recognised that a platform solution was what people were looking for, and we are just integrating or introducing those platforms, market place by market place by market place. It is mobile, entertainment PC, enterprise workspace, and so on. We recognised this several years ago but, because our product development cycles take several years, it has taken us several years to introduce the follow-on.

Lord Broers: We will call the meeting to a halt there. We have worked you very hard but you can see that the questions would have gone on all evening. Let me thank you once again, Dr Barrett, for a magnificent evening. This has been our first international lecture but it will give us a problem in equalling it. Not only was it an exciting lecture about technology and what that can achieve, but it also addressed the social questions. It is marvellous to see your sense of social responsibility and awareness of how these technologies must affect in the most positive way all sectors of society, all over the globe. Thank you for a magnificent lecture. [*Applause*]

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