Some Questions

Why do computers do some things easily that humans find so difficult?

Why do humans (& animals) do some things easily that computers find difficult?

What is intelligence?

What do we mean by an autonomous computer/machine?

What is consciousness?

Can we build a truly intelligent/autonomous computer?

Or, to paraphrase Professor Henry Higgins

- Why can’t a computer be more like a man?
What do computers find easy?

Computers are good at carrying out repetitive, well-defined tasks quickly.

Most computers today are built around the Von Neumann architecture.

Note that processing and memory are temporally and spatially separated.

- Von Neumann bottleneck
What do computers find easy?

Example - computer simulation of a phase-change memory device

Solve three coupled sets of differential equations simultaneously
At each point in space (~ 1 million points here)
At each time step (~ 1000 time steps here)
What do computers find hard?

2010 Loebner Prize

ImageNet Challenge - 2012

How is it going?
A lovely morning to you
What do you think of the weather today?
I wish they'd invent teleportation, then we could live anywhere
Could we live on Jupiter then?
Jupiter has too much gravity, it would squash you flat
Completely flat?
Should I know that?
Are you a man or a woman?
I am woman
Do you like to read books?
Yes, reading is my favourite pastime
Do you like computer animation?
I am not a chatbot
Are you interested in flying kites?
I travel by plane once or twice a year
The Turing Test

Can a machine think?

If a computer could think, how could we tell?

In 1950 Alan Turing suggested that if the responses of a computer were indistinguishable from those of a human, then it might be said to be thinking.

Loebner prize

2011 Loebner Prize results

The 2011 Loebner Prize was held at the University of Exeter on the 19th October.

Judging Panel

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<th>Professor of Artificial Intelligence, University of Sheffield</th>
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<td>Dr Antony Galton</td>
<td>Reader in Knowledge Representation, Exeter</td>
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<td>Paul Marks</td>
<td>Chief Technology Correspondent, How it Works</td>
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<td>Jonny O'Callaghan</td>
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Hugh Loebner pictured showing the Bronze medal presented to the 2011 Loebner Prize winner.
Does Apple’s Siri pass the Turing Test?

And here real speech is used as input, not text!
What Apple can do IBM can do better?

In 2011 an IBM supercomputer ‘Watson’ defeated two ‘Champions of Champions’ in the US general knowledge quiz Jeopardy

2880 parallel processors, 16 TBytes RAM, cost ~ $3 million
IBM’s Watson Computer

Watson received question in electronic (text) form
Voice output synthesised using a text to speech algorithm
200 million pages of content all held in RAM

Computational methods used fairly standard
Making computers more human-like?

We can implement *artificial neural networks* in software on conventional (Von Neumann) computers.

We take inspiration from nature to make a simple computational model of the behaviour of a *neuro-synaptic network*.
Artificial Neural Networks

The ImageNet Challenge – classification and labelling of images
Neural Networks

ImageNet 2012 competition won by an ANN programme call SuperVision
- 650 thousand neurons
- 630 billion synapses

How does this compare to the human vision system?
- 4 billion neurons
- 40,000 billion synapses

Can we approach this kind of scale?

In 2009 IBM demonstrated the simulation of the visual cortex of a cat brain on a Blue Gene/P supercomputer
- ~ 1.6 billion neurons
- ~ 18,000 billion synapses
- ~ 150,000 CPUs
- ~ 150 TBytes of main memory
IBM ‘cat brain’ simulation

Here the approach is to simulate real biological neuro-synaptic activity, not to implement an ANN

Simulation ran *643 times slower* than real time
IBM Blue Gene/Q supercomputer (world’s fastest)

Simulated $53 \times 10^{10}$ neurons and $1.37 \times 10^{14}$ synapses

Ran ~ 150 times slower than real time
Consumed 7 MW of power!

Human brain

~ $10^{11}$ neurons, ~$10^{14}$ synapses
Consumes 10 to 20 W of power!

IBM human brain simulation - 2012
Can we do things differently?

Why use Von-Neumann computer to simulate the brain?
Why not build and artificial brain?
Can we make electronic neurons and synapses?

Not a new idea – suggested by Carver Mead in the 1980s
Use analogue electronics to mimic neuro-synaptic architectures
Often called *neuromorphic engineering/computing*
The Hodgkin-Huxley Neuron

Alan Hodgkin, Andrew Huxley and John Eccles received the 1963 Nobel Prize for Physiology or Medicine "for their discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheral and central portions of the nerve cell membrane".

Hodgkin-Huxley neuron model

\[ I = C_m \frac{dV_m}{dt} + g_K(V_m - V_K) + g_{Na}(V_m - V_{Na}) + g_i(V_m - V_i), \]
\[ I_i = g_i(V_m - V_i) \]
Neuromorphic Engineering

State-of-the-art silicon neuron

Exhibits realistic spiking behaviour
Uses 15 CMOS transistors
Difficulties in scaling CMOS transistors
Power consumption issues
What about synapses?

Need 1000 to 10,000 synapses/neuron
Currently synapses held in ‘remote’ digital memory
Need to fetch synapse weighting from memory for computation
Need to separately update synapse

Processing and storage still temporally and spatially separate
Difficult to attain desired connectivity, speed and power
Device Scaling

Feature Size (microns)

Source: Intel, SIA Technology Roadmap
SIA: Semiconductor Industry Association
Memristor Devices – a new approach

Memristance $M = \frac{\phi}{q}$

- Voltage $V$
- Current $i$
- Capacitance $C = q/V$
- Inductance $L = i/V$
- Charge $q$
- Flux $\phi$

Pre-synaptic neuron
- Synapse
- Impulses
- Axon
- Dendrite

Postsynaptic neuron
- Synapse

Post-synaptic neuron
- Current $i$
- Memristor $M_1$

Forwards current: Higher resistance
Reversed current: Low resistance
Moderate resistance
Types of Memristor

There are many types of memristor

All share some common features
- Can be made very small (sub 10nm)
- Consume very little energy (femto Joules per event)
- Can be fabricated easily into the cross-bar structure for high connectivity
- Can be stacked in 3D for large scale hardware systems

The memristor mimics the strength of the synaptic coupling between neurons
Cross-bar neuro-synaptic device arrays

ANN architecture

Memristor neuronsynaptic architecture

synapse

neurons
Electro-chemical Memristor Synapses

Spike Timing Dependant Plasticity

See Kuzum et al, Nanoletters 2012

Uses a phase-change (not electro-chemical) approach
Phase-change neurons and synapses

The basic phase-change cell possesses

- An accumulation property
- A distinct threshold (for switching),
- A non-linear output transition (of resistance/reflectivity)

Operation is analogous to that of a neuron

- hardware neural networks
- cognitive processors

Possibility of all phase-change neuromorphic computers?

Multiple inputs - constant amplitude (or weighted) pulses

Cell switches (fires) after combination of (weighted) inputs applied
Phase-change devices have potential to be used for far more than just non-volatile memory:

- electronic synapses
- electronic neurons
- brain-inspired computer
- arithmetic processor
- non-volatile logic

### New Scientist (9/7/11)

**Phase-change neurons and synapses**

Phase-change material in DVDs could be the key to unlocking the potential of brain-like computing

Paul Marks

THI material that lets us record on DVDs has a far more tantalising property: it can mimic the nerve cells of the brain and the junctions between them. The discovery could lead to the development of brain-like computers that, crucially, operate at ultra-low power levels.

Brain-like computers are those that can learn and adapt without external programming. Such an ability would allow machines to become far better at tasks like face and speech recognition. They could also process more data.

“A build-up of input signals makes the alloy change state, just as a real neuron fires at a certain threshold”

In the same location—just as nerve cells do. Conventional computing wastes energy by keeping these functions separate. Now two research groups have built artificial nerve cells, or neurons, and synapses—the junctions between them—using an alloy known as GST, an acronym of the symbols for its components: germanium, antimony and selenium.

In the UK, David Wright and colleagues at the University of Exeter have created a GST neuron (Advanced Materials, DOI: 10.1002/adma.201002606), while at Stanford University in California, Philip Wong’s group have created a non-volatile electronic synapse. The junction even mimics the way synapses can change their connection strength (Nano Letters, DOI: 10.1021/nl301398m).

GST is known as a “phase-change” alloy, because of its ability to change its molecular structure from a crystalline to a disordered amorphous “phase” when heated. In DVDs, this allows binary 1s and 0s to be recorded and then read by a laser.

But GST can do more than store data in different areas within a tiny spot of GST can be crystalline or amorphous at differing degrees, which means it can store information across an array of wider range of values than simply 0 or 1. This importance because it is a build-up of input signals that makes a real neuron “fire” when it reaches a certain threshold.

Wright’s team was able to mimic this threshold firing because GST’s electrical resistance drops suddenly when it moves from its amorphous phase to the crystalline. So incoming signals in the form of pulses of current are applied to the artificial synapse, and it is deemed to have fired when its resistance plummet.

GST’s talents don’t end there. When a real neuron fires, the signal’s importance to the next neuron it arrives at is set by the strength of the synapse connecting them. In nature, this strength is adjusted in a process called spike-time-dependent plasticity (STDP). If the first neuron unexpectedly fires before the second, the synapse’s strength increases; if the second fires first, its strength decreases.

Fergil Kormus, a member of the Stanford team, says GST’s ability to change its resistance has allowed them to program it to dynamically modify the strength of the nanoscale artificial synapse they have built—just like LTD. This lets them prioritise which neural signals are most important to any task. At just 2 nanometers across, the artificial synapse may offer the low power needed for brain-like computers, says Kormus. The team’s calculations suggest a system with 10^10 synapses would consume just 20 watts—a contrast with the 1.4 megawatts used by a supercomputer to simulate just seconds of brain activity.

Phase-change devices may indeed capture the right essence of the behaviour of the brain,” says Thor Purcell of the University of Manchester, UK, who is building brain-like computers from conventional microprocessors. “But it has a very long way to go. I’ll be interested when they can make 10^10 of them on a chip for next to nothing.”

9 July 2011 | New Scientist

### Financial Times (2/7/11)

**‘Brain-like’ machines come closer**

A new type of electronic component, which combines memory storage with information processing, has been developed at Exeter University.

If the technology can be scaled up, it could be used to make computers more “brain-like,” as well as increasing their speed and energy efficiency.

Computers currently deal with processing and memory separately, causing a speed and power bottleneck as data moves between the two activities. In human brains, however, no real distinction is made between memory and computation.

To perform both functions at once, the Exeter researchers used a “phase-change” semiconductor made from a three-way alloy of germanium, antimony and tellurium. This undergoes a huge change in electrical and optical properties as it changes between amorphous and crystalline states.

The study, published in the Journal of Advanced Materials, demonstrates that phase-change materials can store and process information simultaneously. It also shows experimentally that they can perform arithmetical operations.

More strikingly, the research shows that phase-change materials can be used to make artificial neurons and synapses. In theory an artificial system made from phase-change devices could learn and process information like a living brain.

“We have uncovered a technique for potentially developing new forms of ‘brain-like’ computer systems that could learn, adapt and change over time,” says David Wright, project leader. “This is something researchers have been striving for over many years.”

This study focused on the performance of a single phase-change cell. The next stage will be to build systems of interconnected cells that can learn to perform simple tasks, such as identifying patterns.

“You could imagine an artificial brain made of an array of phase-change materials, some acting as neurons and some as synapses,” Wright says.

9 July 2011 | New Scientist
The Human Brain EC FET Flagship Project

€1 billion, 10 year project

- **NEUROSCIENCE**
  - Physical model neuromorphic system implementing 10 trillion hardware synapses
  - NMCP4

- **MEDICINE**
  - Numerical many-core neuromorphic system handling 100 billion spikes/sec
  - NMCP3

- **FUTURE COMPUTING**
  - Numerical many-core neuromorphic system handling 10 billion spikes/sec
  - NMCP2

  - Physical model neuromorphic system implementing 5 billion hardware synapses
  - NMCP1

Timeline:
- **2013**
- **2023**
The human organisation has produced an 8-point Transhumanist Declaration.

The first four points seem relevant here

1. Humanity stands to be profoundly affected by science and technology in the future. We envision the possibility of broadening human potential by overcoming aging, cognitive shortcomings, involuntary suffering, and our confinement to planet Earth.

2. We believe that humanity’s potential is still mostly unrealized. There are possible scenarios that lead to wonderful and exceedingly worthwhile enhanced human conditions.

3. We recognize that humanity faces serious risks, especially from the misuse of new technologies. There are possible realistic scenarios that lead to the loss of most, or even all, of what we hold valuable. Some of these scenarios are drastic, others are subtle. Although all progress is change, not all change is progress.

4. Research effort needs to be invested into understanding these prospects.

Or, to quote Isaac Asimov

The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom
The end?
Exeter – post and pre-human