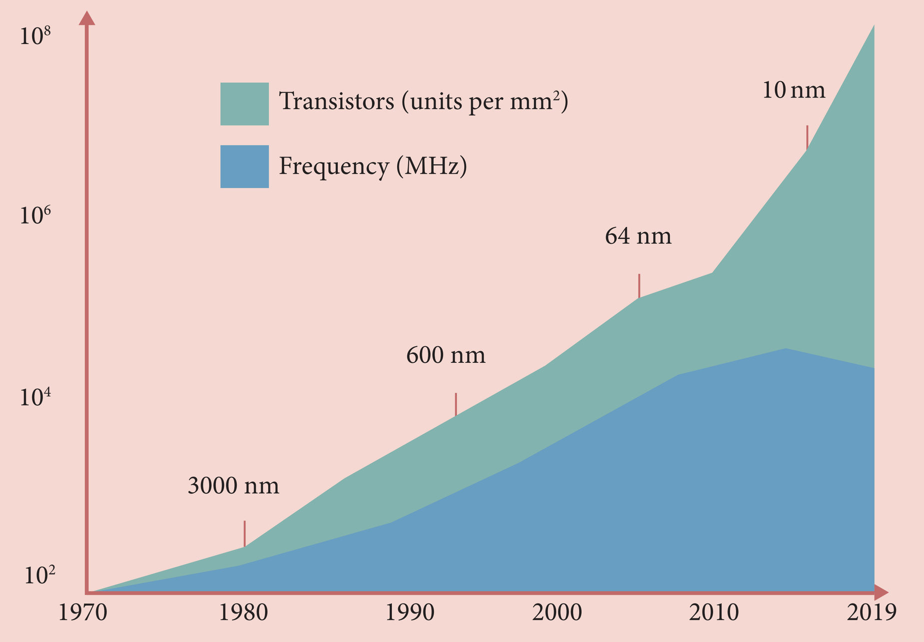
Pushing Moore's Law with Bio-inspired computing

Authors: Hilde Meussen Elholm, Petter Grønlie and Brynjar Morka Mæhlum

We are reaching the limits of Moore's Law

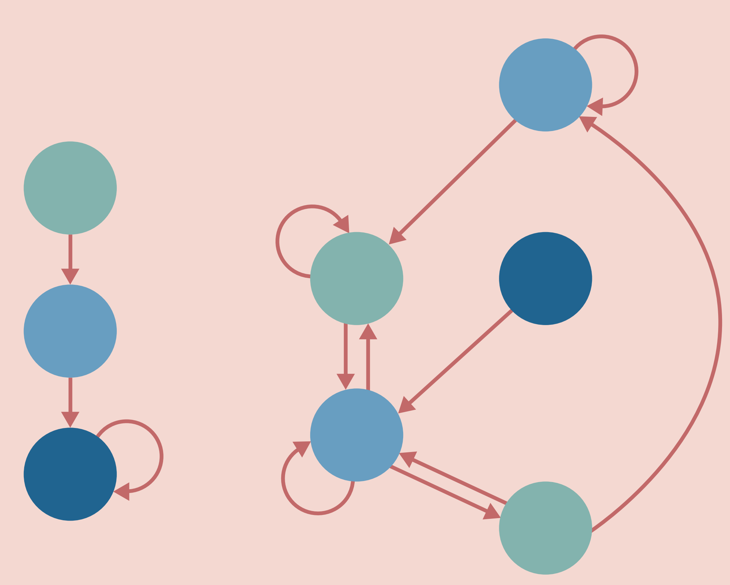
Moore's law states that the amounts of transistors per area would double for every second year. Amazingly, we have managed to keep up with this prediction since it was first made in 1965.
Unfortunately, we are soon reaching a point where our transistors are so small that we are entering the strange and unpredictable realm of quantum mechanics. Even though it is possible to make the transistors somewhat smaller, the power we put into the traditional computer chips have already reached a maximum. More power would literally melt the chip. Not being able to cram more transistors into a small space means we need to think of new, more effective ways of computing to keep up with our current pace of progress.
Might mimicking biological systems be the solution?



Graph depicting maximum possible amount of transistors on a chip. Notice how the frequency peaked during the last decade. A higher frequency requires more power, and therefore the frequency had to be lowered in order to allow for more transistors.

How might biology inspire computers?

Many biological systems, such as a colony of ants or a human brain, have a **fine-grained architecture**. This means that they are made up of a large amount of relatively simple units. In different systems these units interact quite differently, but these interactions have some basic similarities. The units operate at the same time and in parallel. This is a huge contrast to how classical computers work today, which often use a sequential process, overseen by a Central Processing Unit (CPU). In many biological systems, no single unit or group of units act as a "leader", or a CPU. Every single unit interacts with its environment based on randomness and probabilities.
To balance random actions, biological systems utilise **feedback loops** to adapt to its environment. This can be by changing the probability of an action taking place, such as lowering the membrane potential of a neuron, making it less likely to fire off a signal. Another way to adapt is to physically change the system, such as creating a new connection between two neurons.
Many biological systems have the abilities to change both their "hardware" and their "software" by performing actions such as the ones described. Systems with the capability to change themselves in this way are called "dynamical systems with dynamical structures" or **DS^2**.



*Sequential structure versus DS^2.
The sequential structure follows a static path, whereas the nodes in the DS^2 can influence eachother dynamically.*

Cyborgs are teaching us how to compute

To learn how to recreate the human brain's robust and energy-efficient way of computing, scientists at NTNU are creating **real-life cyborgs**. By growing human neurons from induced stem cells in vitro over Micro-Electrode Arrays (MEA), studying how they behave is made possible. The MEAs can read and deliver electrical signals to the brain cells growing on them, and teach us more about how the brain works. Such a set up could even perform computations!
Once we know more about how the neural network works, we can try to mimick their behaviour using inorganic materials, such as nanomagnets. **The goal is to create a computer able to make computations in much the same way as a brain does.** In the future bio-mimicking computers might have the ability to change its own hardware, just like a brain can!

Neurons on a chip from an NTNU-lab.

Definition: Neuromorphic

Neuromorphic solutions means any very large-scale system of integrated circuits that mimic neurobiological architectures present in the nervous system.[2]

Why Bio-Inspired computing?

Neuromorphic computers open the door to superefficient computing. The human brain with its fine grained architecture dissipates 10-30 Watts. In comparison Tesla's Full Self-Driving Computer (FSD) uses up to 72W[1]. It works by running an image recognition algorithm on traditional sequential chips. In other words: the human brain spends a lot less energy driving a car compared to Tesla's FSD.
Even though they may be superefficient, neuromorphic computers will probably be restricted to some type of computations. Running Mac, Windows or Linux operating systems will not be possible on a neuromorphic chip, but using them to perform complex computations such as **image recognition, big data handling and simulations** in a better and more efficient way looks promising. A computer which is a dynamical system with dynamical structures might also open unknown doors to **new types of computing**.
One example of a new type of computing: instead of granting a computer "artificial intelligence", such as Tesla's FSD has, we might give a computer **"common sense"**. An algorithm running on sequential hardware might be trained to perform certain tasks, but this requires a lot of examples. The algorithm simply lacks common sense!
Now consider this scenario: At St. Olavs, Doctors wish to develop an algorithm for recognizing a certain type of cancer. This type of cancer might be rare, or it might take time to create an image of the cancer. In this case, an "artificial intelligence"-algorithm falls short, as it needs millions of images to be trained. Imagine needing to show just a few pictures of the cancer types to the algorithm, instead of millions. An algorithm with "common sense" could then infer from these pictures, just like the human brain can. This could be possible with a DS^2 fine-grained architecture.

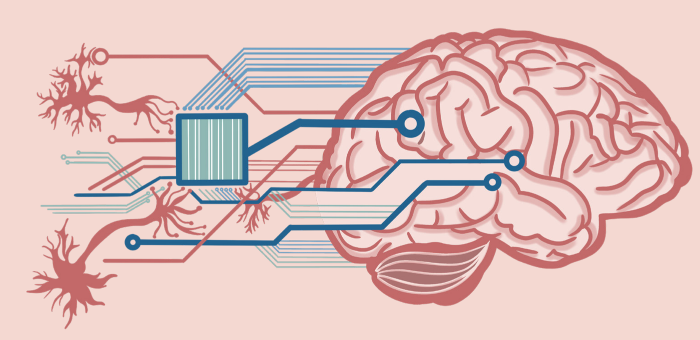
Ethical implications

Losing control
An issue arises when considering how a DS^2 might act if left to itself. If no restrictions are put on it, it might "evolve" both its hardware and software autonomously, and become something different to what it was originally intended to be. In a worst-case scenario we might lose control over our computer. Incorporating some kind of dead man's switch might be a good idea!

Creating DS^2
The mechanisms of dynamical systems with dynamical structures where "hardware" changes "software" and vice versa are part of the definition of a living organism. Changes to the DNA of living organisms have been approved by the EU to certain limits. By the law, computers with a DS^2 are no different than GMOs and therefore neuromorphic computers have been approved by the EU.

Integrity of life on a chip
Other ethical implications are tied to the research of wetware and cyborgs. Creating a cyborg with human neurons might simply not sit well with people. An important thing to consider here is how far we should allow these "brains on a chip" to develop.

Energy efficiency
Neuromorphic solutions might improve energy-efficiency by several orders of magnitude[2]. An example of this is that the use of nanomagnets in bio-inspired computers have the benefit of not using energy while the data is stored. Traditional data storage needs energy, and in 2018 data storage alone used approximately one percent of the world wide electricity use[3]. Nanomagnets in computers are still at research level, but are a promising type of neuromorphic computers.



TL;DR

As we are approaching the limits of how fast and efficient sequential computer chips with transistors can be, we need to start thinking of new designs in order to continue to increase computational power.
A solution to this is to create computer chips inspired by how biological systems process and act on information. The resulting computer might be able to change its own hardware just like the human brain can change its structure by creating new connections between neurons.
Creating computers able to change their own hardware and utilising a parallel, fine-grained architecture could be a powerful tool in advancing our ability to perform certain tasks such as image recognition in a better and more energy-efficient way.

Sources

Conversation with Gunnar Tufte, professor at the Department of Computer Science at NTNU

Conversation with Isak Kyrre Lichtwarck Bjugn, masters student at Department of Neuromedicine and Movement Science at NTNU

Mitchell, M. (2009). Chapter 12: Information processes in living systems *Complexity: a guided tour* New York: Oxford University press, p. 169-185

Aaser, P et al. (2017) *Towards making a cyborg: A closed-loop reservoir-neuro system.* Massachusetts Institute of Technology. Available at: http://cognet.mit.edu/proceed/10.7551/ecal_a_072 (Retrieved: 16.04.2020)

1. *FSD Chip - Tesla* (without date) Available at: https://en.wikichip.org/wiki/tesla_(car_company)/fsd_chip (Retrieved: 16.04.2020).
2. European Commision. (2020) *On artificial intelligence - A European Approach to Excellence and Trust* Brussels: European Commision.
3. Sverdlik Y. (2020) *Study: Data Centers Responsible for 1 Percent of All Electricity Consumed Worldwide.* Available at: https://www.datacenterknowledge.com/energy/study-data-centers-responsible-1-percent-all-electricity-consumed-worldwide (Retrieved: 16.04.2020).

Photos:
Brain Mannequin: David MatosW
Neurons on chip: Kai T. Dragland, NTNU
Illustrations and graphs by Petter Grønlie