Dreaming as Physics go...

An imaginary journey towards the limits of detection and imaging.

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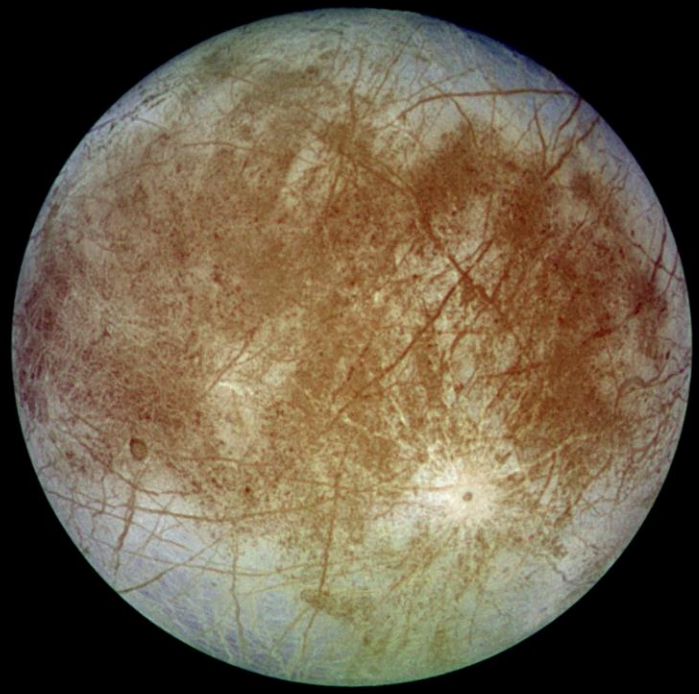
Europa

Europa...the smallest of the four Galilean moons orbiting Jupiter.

Discovered in 1610 by Galileo Galilei and named after the Phoenician mother of King Minos of Crete and lover of Zeus.

Made of silicate rock, a water-ice crust and with a very thin atmosphere, composed primarily of oxygen.

The apparent youth and smoothness of its surface have led to the hypothesis that a water ocean exists beneath it, which could conceivably harbour extra-terrestrial life.



The Mission

The year is 2070.

The Search for Extra-Terrestrial intelligence institute (SETI) in collaboration with all Space Agencies of the world have been commissioned the mission of exploring Europe.

The objectives are:

- Finding if Europa might be suitable for life in the hope of establishing a new habitat for humankind in the coming years.

- Exploring, if life exists already, its main characteristics in a sustainable and ethical manner.

The mission should be completed as fast as possible. The degradation of Planet Earth cannot wait for mitigation measures only.

Another humankind post must be found soon for moving there temporarily and allowing our planet recovering from human activity...and Europa seems to be the best candidate nearby.

The Plan

How would it be possible to fully explore the oceans of Europa in a short time and with maximum efficiency?

The SETI scientists and engineers have decided sending a unique vehicle, that in a single mission, deploys thousands of micro-robots capable of sensing the entire oceans.

They should be as small as possible but:

- Not so small that they cannot swim towards interesting signals sources such as light, temperature, chemicals, etc.

- Equipped with a minimum computing unit for storing and sending information to the Europa's orbiting vehicle for transmission to Earth.

The Physics Limits

The SETI scientists and engineers have consulted with biophysicists who gave them this table:

Stimulus	Mechanism	Constraint formulas	$2r$, μm
None	Diffusion	$\frac{D_m}{D_0} = \left(\frac{4\pi\eta}{kT}\right)^2 \left(\frac{1}{2}\right) u^2 r^6$	0.64
Chemical	Spatial	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{1/2} (2\pi DC)^{1/2} \left(\frac{3}{L}\right) r^3$	0.58
Chemical	Temporal	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{3/2} (2\pi DC)^{1/2} \left(\frac{u}{L}\right) r^6$	0.65
Light	Spatial	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{1/2} (2\pi If)^{1/2} \left(\frac{2}{L}\right) r^{7/2}$	1.77
Light	Temporal	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{3/2} (4\pi If)^{1/2} \left(\frac{u}{L}\right) r^{13/2}$	1.05
Light	Direction	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{1/2} (\pi If)^{1/2} \alpha r^{7/2}$	1.24
Temperature	Spatial	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{3/4} \left(\frac{(4\pi H_T)^3}{k^2 H_c}\right)^{1/4} \left(\frac{2}{L}\right) r^{13/4}$	0.74
Temperature	Temporal	$\frac{S}{N} \leq \left(\frac{4\pi\eta}{kT}\right)^{7/4} \left(\frac{(4\pi H_T)^3}{k^2 H_c}\right)^{1/4} \left(\frac{u}{L}\right) r^{25/4}$	0.69

Don’t panic!!! The SETI folks did as well initially. This is how the biophysicists told them to read the table (next slide)

The Physics Limits

Stimulus	Mechanism	Constraint formulas	$2r$, μm
	Minimum diameter size for a micro-bot capable of swimming towards a...		
Chemical	... chemical signal that is spread spatially in water.		0.58
Chemical	... chemical signal that is spread in time in water.		0.65
Light	... light signal that is spread spatially in water.		1.77
Light	... light signal that is spread in time in water.		1.05
Light	... light signal that changes its direction in time in water.		1.24
Temperature	... temperature signal that is spatially spread in water.		0.74
Temperature	... temperature signal that is spread in time in water.		0.69

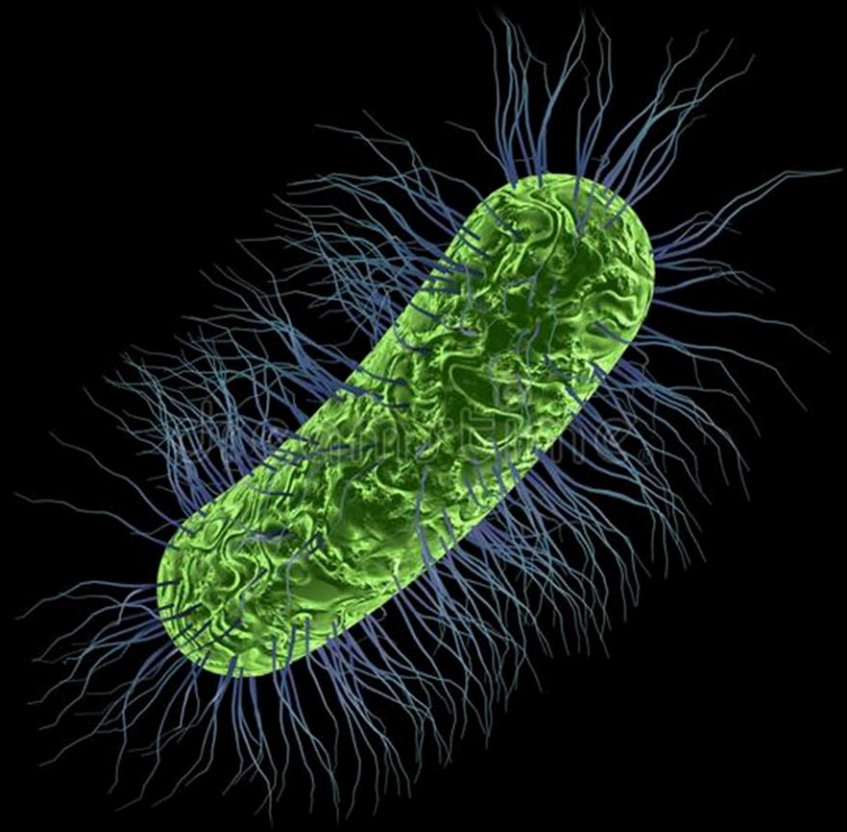
The Inspiration of Biophysicists

Of course, the SETI folks were amazed so they asked the biophysicists where these micro-bots size limits came from…

The biophysicists explained:

We took the physics equations of movement in a fluid like water as well as the threshold of any signal on it for being perceived against noise.

And the interesting thing is that we came up with micro-bot size limits similar to bacteria…which is itself a micro-bot!!!!



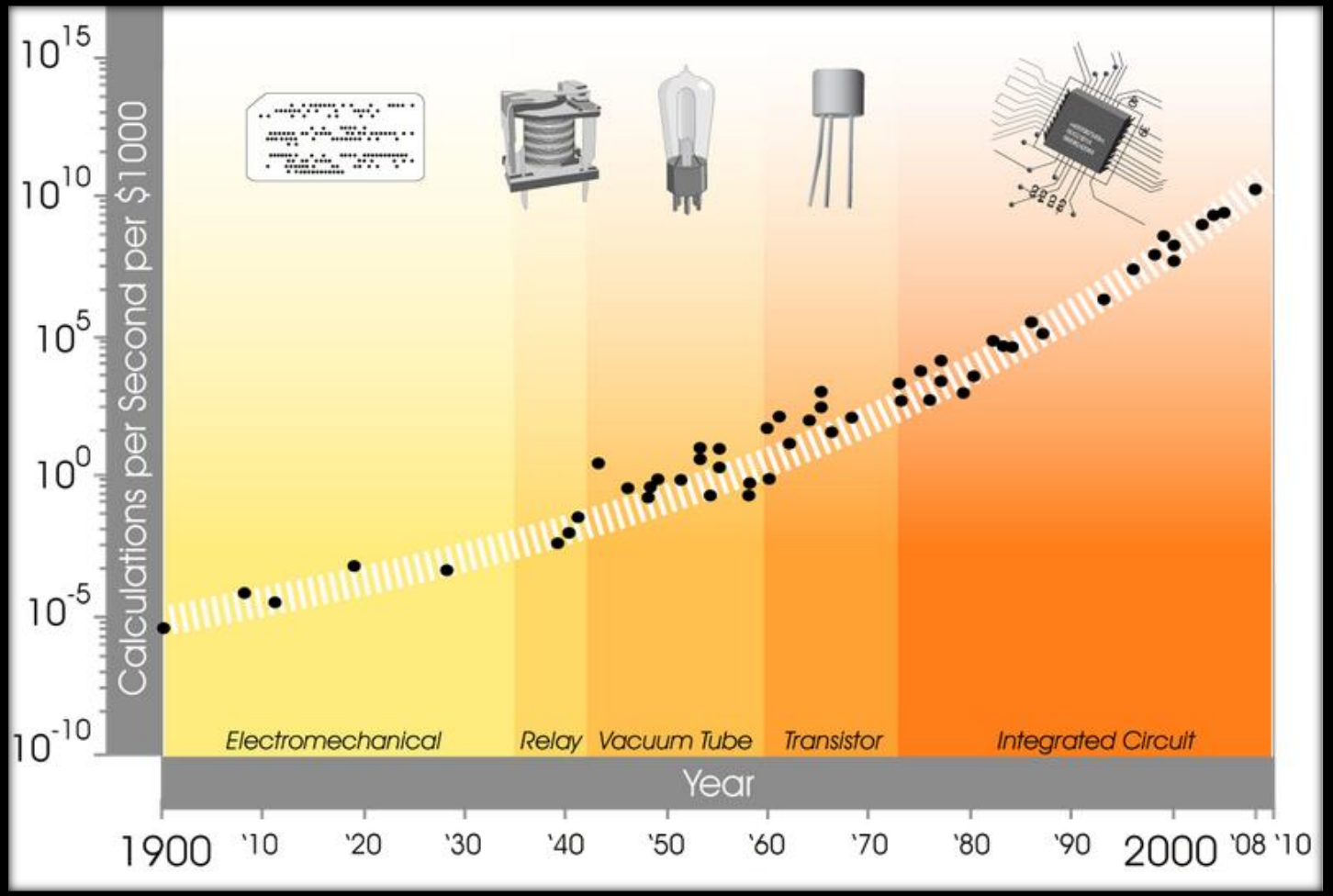
The Technology Challenge continued though…

The SETI folks organized an internal meeting:

Now we know how big the micro-bots should be for sensing and swimming… but what about computing?

What is the minimum computer that we can achieve with the technology we have today even if we take it to the limit?

They put a special team hands on for calculations… they called themselves the "Mavericks".



The Mavericks report…(1)

After intense days of hard work and many coffees, the Mavericks presented the rest of the team the following table. Immediately they got the question:

Guys, what do we read here? What is the essential message?

	Logic	Memory
F_{min} (nm) (critical feature size)	4.5	10
n_{2D} (cm^{-2}) (logic density)	5×10^{11} ($1/8F^2$)	2.5×10^{11} ($1/4F^2$)
V (volts)	0.65	5 (read)/ 15 (write)
E_{bit} (Energy/bit)	3×10^{-18} J ~ 1000 k_BT	~ 10^{-13} J ~ 10^7 k_BT (read) ~ 10^{-12} J~ 10^8 k_BT (write)
P_{leak} (W) (power consumption by leakage currents)	2×10^{-9}	low
n_{3D} (cm^{-3}) (logic density)	1.5×10^{17} ($1/72F^3$)	4.2×10^{26} ($1/24F^3$)

The Mavericks report… (2)

The Mavericks explained:

After considering the physics laws that make electronic chips work and take them to the limit… we have good news and bad news… good first:

Yes, we can make very small chips for fitting a tiny memory in the micro-bot. Here you guys see that the size of a single chip of this memory would be as small as 10 nm. Imagine! 10,000 times thinner than human hairs.

And the bad?

Well, first we would not be able to have a lot of memory space in a our micro-bots since although 10 nm per chip is very small our micro-bots are micrometer size. We cannot store many 0s and 1s since each one of these chips should store either a 0 or a 1. Remember 1 micrometer is only 1000 nm and our micro-bots should be at least 0.58 micrometers according to the biophysicists. Thus, not many chances to get a lot of info per micro-bot about Europa's oceans.

Second and worst, our memory consumption will be too high because we need 15 V of current for writing 0s and 1s.

A big silence filled the meeting room…

	Logic	Memory
F_{min} (nm) (critical feature size)	4.5	10
V (volts)	0.65	5 (read)/ 15 (write)

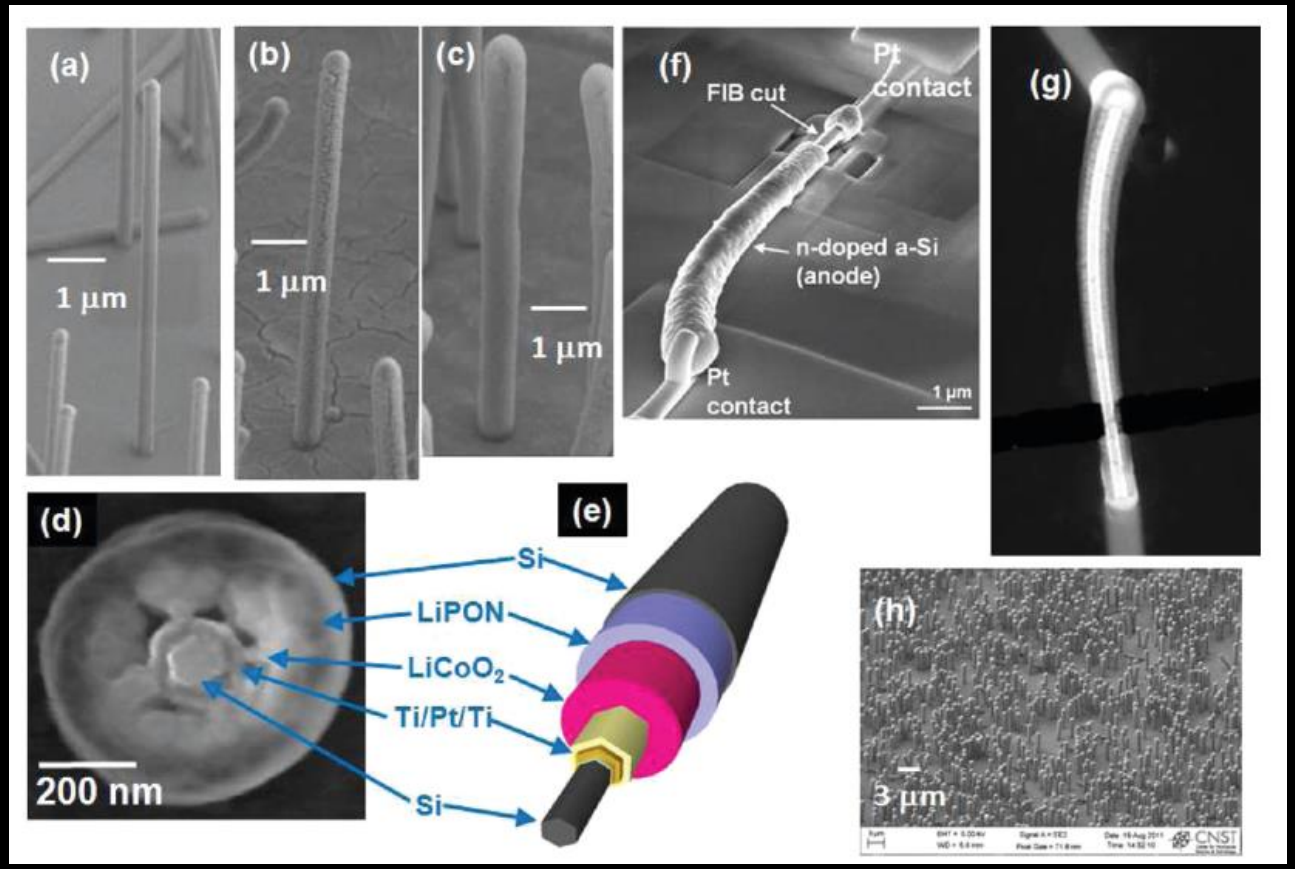
The Mavericks report... (3)

The Mavericks chief engineer intervened:

Well, the problem of memory storage capacity per micro-bot might be worked around by sending an enormous amount of them... but the energy consumption is a big issue... how could we autonomously power the micro-bots if they need such high currents for writing 0s and 1s?

Nano-battery miniaturization technology is merely in its infancy. Although nano-battery prototypes have been achieved as small as 100 nm they suffer from rapid self discharge. Actually they can only deliver 2 V for over 2 h...our micro-bots will be dead and useless in no time...moreover, the power delivered by the battery must be used primarily for making the micro-bot swim and not for memory and computing...

Just to be sure about our constraints, please Mavericks perform a calculation of the smallest computer possible and come back for discussion.



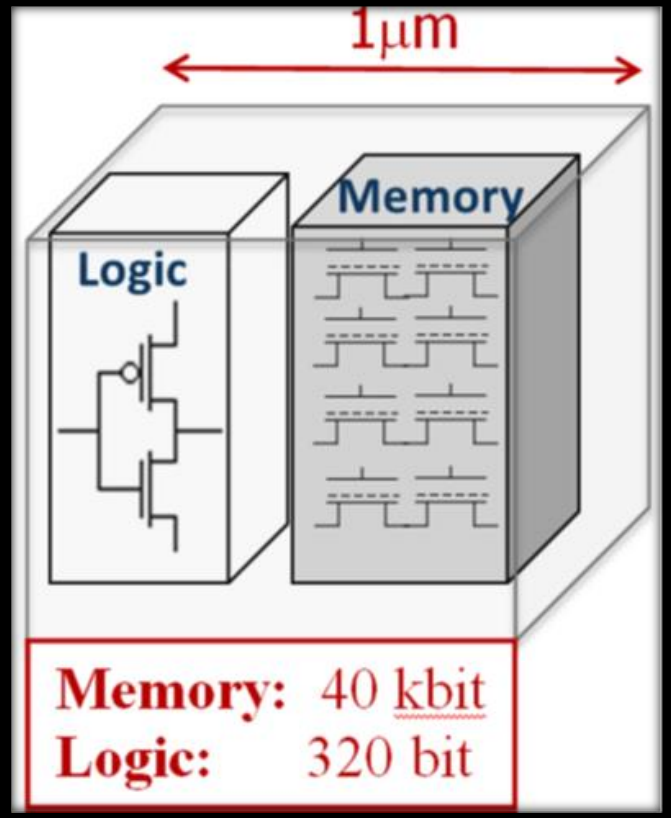
The Mavericks new report… (1)

The Mavericks team went to the drawing board and performed a more comprehensive calculation targeting the ultimate computer by extrapolating to the limits the available technology.

In the meeting day, they showed the rest of the team this figure and a table:

Again folks, what do we read here?

As you may imagine, this question was already expected…



	Logic	Memory
F_{min} (nm)	4.5	10
N	320	40000
E_{bit} (J/bit)	3×10^{-18}	~ 10^{-15} (read)
E_{cycle}	~ 10^{-15}	~ 10^{-13} (read)
F_{clock} (MHz)	100	
P_{active} (W)	10^{-7}	10^{-5}
P_{leak} (W)	6.4×10^{-7}	assumed low
P_{total} (W)	~ 1.1×10^{-5}	
Q_{active} (W/cm2)	1.7	167
Q_{leak} (W/cm2)	11	assumed low
Q_{total} (W/cm2)	~ 180	

The Mavericks new report... (2)

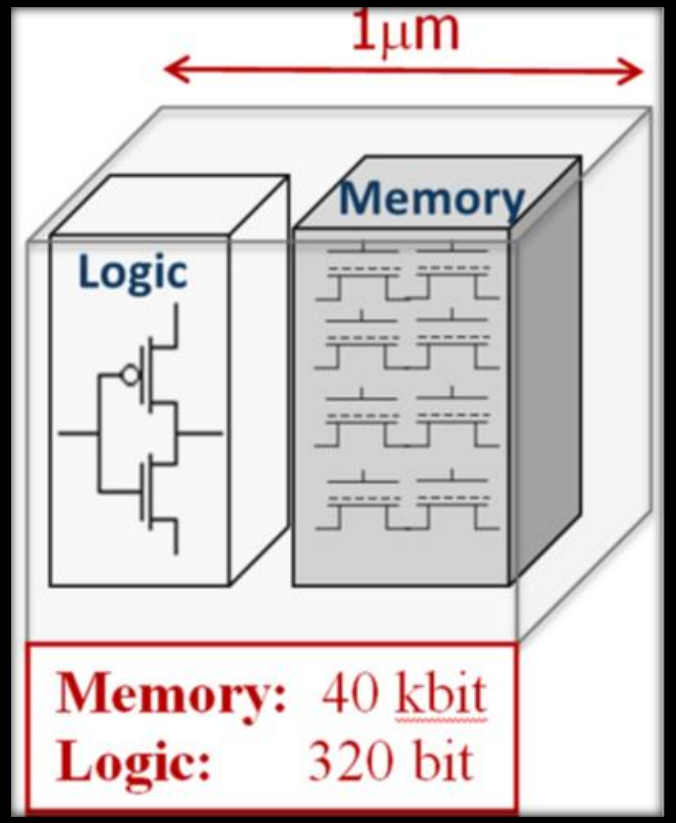
The Mavericks explained:

What you guys see here is a model of what we call the ultimate micrometer size computer.

We have targeted for a cube of 1µm3 Si-based computer containing 320 logic transistors and 40 kbit of memory. This is the minimum needed for what is known as the most simple computation cycle. In other words, something similar to our micro-bot sensing once, storing the info in its memory and sending it to the Europa orbiting vehicle.

We are afraid that the key numbers here show again that it will consume too much power.

A desperate silence could be cut with a knife in the room.



	Logic	Memory
E_{bit} (J/bit)	3×10^{-18}	~ 10^{-15} (read)
E_{cycle}	~ 10^{-15}	~ 10^{-13} (read)

A New Inspiration from Biology

The power consumption problem obliged exploring new avenues and consulting with fellow scientists from every possible discipline.

The biologists came up with some numbers indicating that eventually the problem could be solved.

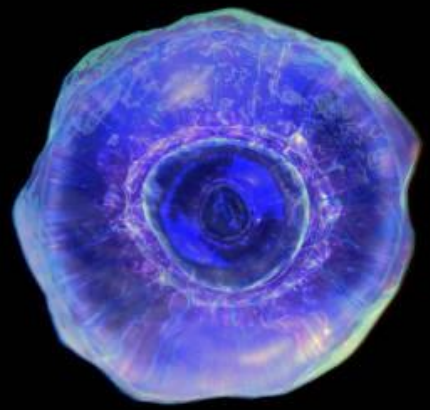
It would required though from the physicists and engineers embarking in the most amazing challenge they have ever faced…

During the meeting day, the biologists showed this…

…and you can imagine what the first question was.

Parameter	"Ultimate Si µ-Cell"		Real µ-Biological cell	
	Logic	Memory	Logic	Memory
Density	10^{17} cm^{-3}	10^{16} cm^{-3}	10^{18} cm^{-3}	10^{19} cm^{-3}
Energy/bit	10^{3} k_BT	10^{8} k_BT	<10 k_BT	<10^{4} k_BT
Power	10^{-7} W		10^{-13} W	
Heat Flux	1 W/cm^2		10^{-6} W/cm^2	
Energy per 10^{11} output bits	10^{-2} J		< 10^{-9} J	
Time to compute 10^{11} output bits	10^{5} s		10^{3} s	

The Biologists Presentation (1)



The biologists explained:

At the top, you guys see a picture of a human cell: the ultimate micrometer size computer!

At the bottom you see a comparison between what a human cell does and what your micro sized silicon based computer would do for the same task.

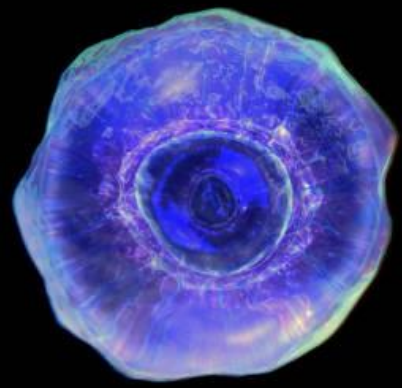
The benchmark task is equivalent to providing an information output of 1011 bits (the amount of information estimated that needs to be generated by the "cell processor" to build a new cell).

The SETI team asked again:

Very nice, but what is the key message?

Parameter	"Ultimate Si µ-Cell"		Real µ-Biological cell	
	Logic	Memory	Logic	Memory
Density	10^{17} cm^{-3}	10^{16} cm^{-3}	10^{18} cm^{-3}	10^{19} cm^{-3}
Energy/bit	10^{3} k_BT	10^{8} k_BT	<10 k_BT	<10^{4} k_BT
Power	10^{-7} W		10^{-13} W	
Heat Flux	1 W/cm^2		10^{-6} W/cm^2	
Energy per 10^{11} output bits	10^{-2} J		< 10^{-9} J	
Time to compute 10^{11} output bits	10^{5} s		10^{3} s	

The Biologists Presentation (2)



The biologists continued:

As you see, the human cell can compute all these bits using a ridiculous amount of energy, actually six orders of magnitude less than you micro computer.

And not only that…it does it in much less time, therefore dropping even more any battery consumption.

If Mother Nature has achieved it…why not us?

That was the spark needed!!

Parameter	"Ultimate Si µ-Cell"	Real µ-Biological cell
Power	10^{-7} W	10^{-13} W
Energy per 10^{11} output bits	10^{-2} J	< 10^{-9} J
Time to compute 10^{11} output bits	10^{5} s	10^{3} s

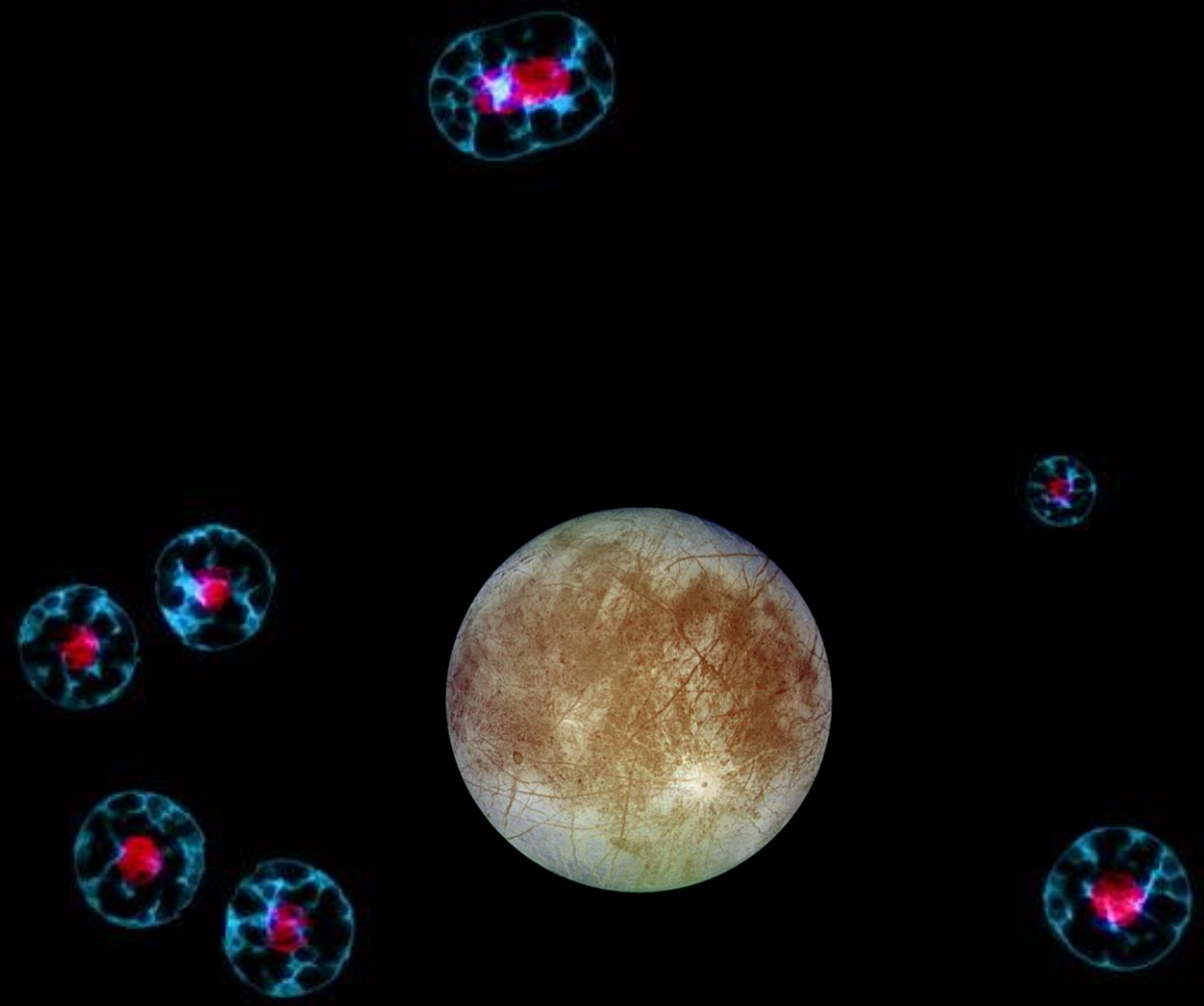
The challenge was clear and audacious: building a cell-like computer.

The road turned more bumpy than expected but it was worthwhile.

Thousands of micro-bots were sent to Europa...

...and its oceans, although lacking life, have proven to be our new temporary home that will allow our Planet Earth recovering from us...

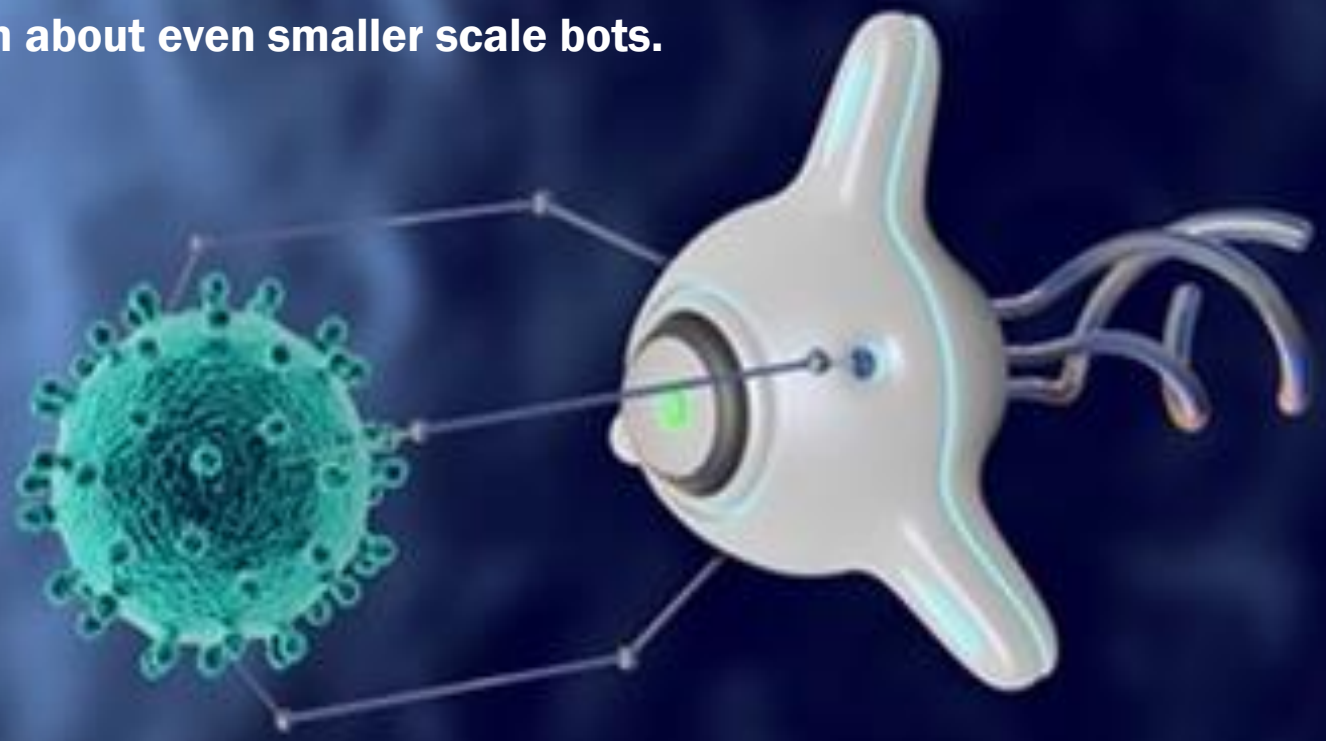
...until we come back anew and hopefully having learned the lessons.



The newly developed micro-bots, once used for exploring the Cosmos, opened new possibilities unimaginable before...

...specially because they were capable of storing enough information for self-replication.

They also allowed us to dream about even smaller scale bots.



The question still is...

...would they make us better humans?

See you soon!

For the curious…

If you want initiating yourself in the wonders of scaling with barely any math:

- J. T. Bonner, *Why Size Matters: From Bacteria to Blue Whales,* Princeton University Press, 2011.
- T. P. Smith, *How big is big and how small is small: The Sizes of Everything and Why,* Oxford University Press, 2013.

If you have a college math background and you are interested in scaling and on how small animals move:

- E. M. Purcell, *Life at low Reynolds number, American Journal of Physics 45, 3 (1977).*
- M. Denny and A. McFadzean, *Engineering Animals: How Life Works,* Harvard University Press, 2011.

If you have a first university year math level and you are interested in scaling and how small animals move:

- H. C. Berg, *Random Walks in Biology,* Princeton University Press, 1984.
- K. Schmidt-Nielsen, *Scaling: Why animal size is so important,* Cambridge University Press, 1984.
- C. S. Cockell, *The Equations of Life: How Physics Shapes Evolution,* Basic Books, 2018.

For the curious…

If you have a full degree of math university level, physics and/or engineering:

- *D. B. Dusenbery, Minimum size limit for useful locomotion by free-swimming microbes, Proc. Natl. Acad. Sci. USA, Vol. 94,, September 1997. (This is the article I used for the table of the biophysicists).*
- *F. G. Barth and A. Schmid (Eds.), Ecology of Sensing, Springer, 2001.*
- *F. Cleri, The Physics of Living Systems, Springer, 2016.*

These articles have been my basis for the elaboration of the Mavericks and the Biologist's tables

- *Victor V. Zhirnov et al., Proceedings of the IEEE, vol. 91, No. 11, November 2003, (and references therein).*
- *Laszlo B. Kish, Physics Letters A 305 (2002) 144–149.*
- *Y. Li et al, Fluctuation and Noise Letters, vol. 6, No. 2 (2006) L127–L131.*
- *Victor V. Zhirnov et al., Solid-State Electronics 54 (2010) 810–817.*
- *Ralph K. Cavin III, et al., Proceedings of the IEEE, vol. 100, May 2012.*

The nano-battery plot and performance is taken from

D. Ruzmetov et al., Nano Lett. Vol. 12, 2012.