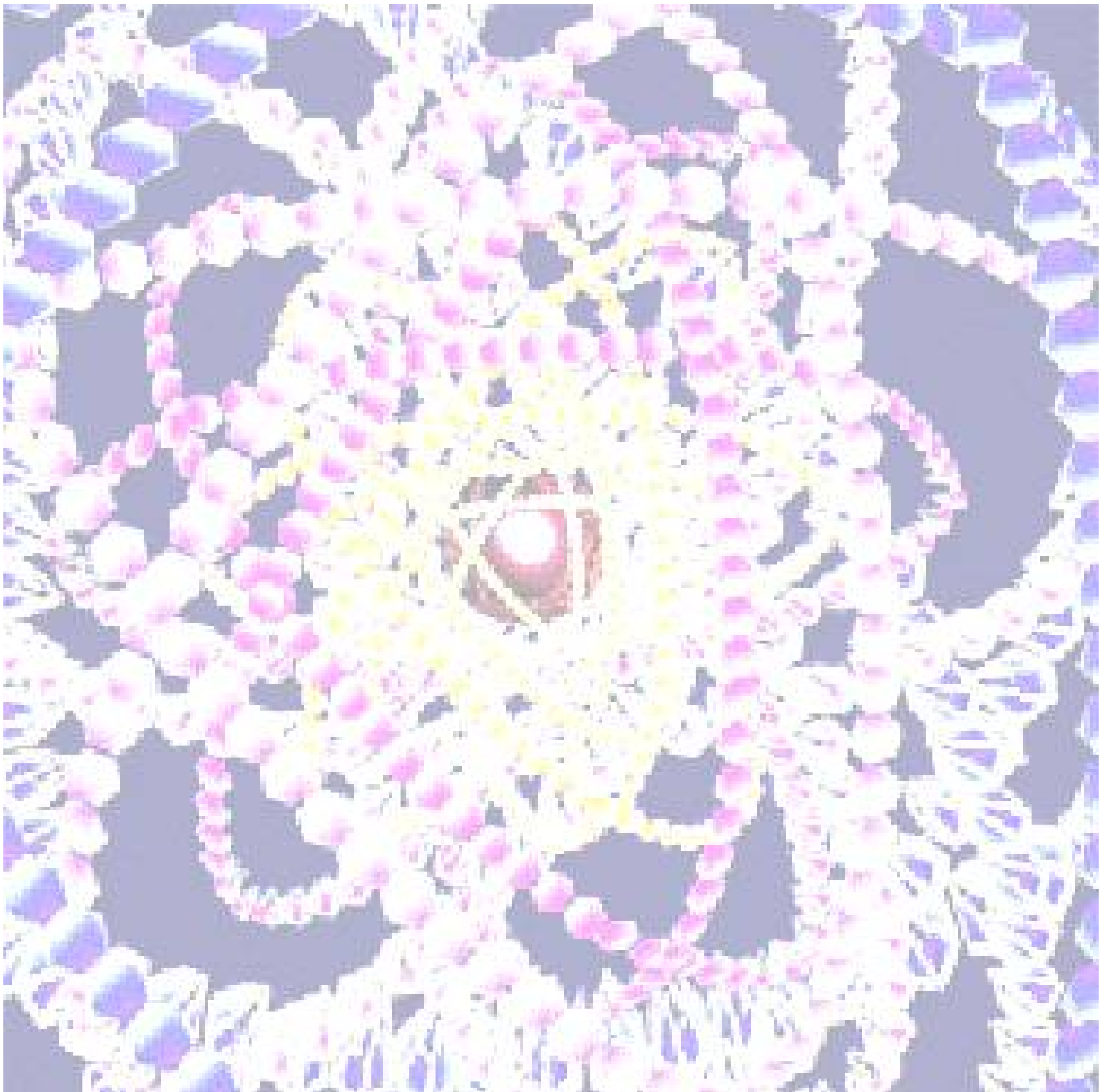
Matrioshka Brains – Some Intermediate Stages in the Evolution of Life

The name is taken from "Matryoshka[1]" – those Russian dolls embedded in each other – because it might be expected that these brains might be shells of matter embedded within each other.

[1] This attached picture is taken from http://www.natashascafe.com/html/doll.html.


An artist's conception of what such a brain may look like[2].

Sometimes the literature refers to them as "Jupiter brains" – they need not necessarily be shells, but can be constructed of a different architecture or materials.

- A solid or semi-solid "diamandoid" structure – consisting of atoms and molecules at normal (everyday) densities.
- A solid structure made of degenerate matter – this material could be supported through electron or neutron degeneracy

[2] Artist's conception is taken from http://www.aeiveos.com/~bradbury/MatrioshkaBrains/MatrioshkaBrains.html#KardashevCivilizations.

pressure (remember Pauli exclusion principle). This provides huge orders of magnitude increase in information density, processing speeds, and bandwidths.

- The shell of normal matter surrounding a star or other energy source?
- Black holes – it is believed they can store information and process it as well, using the laws of thermodynamics.

These “brains” are essentially megascale computers operating (so it is believed) at a capacity at or very near the physical or thermodynamic limits of their constituent materials, OR EVEN AT THE LIMITS PLACED BY THE UNIVERSE ITSELF – THE BEKENSTEIN LIMIT.

Important Aspects of Matrioshka (or Jupiter) Brains[3]

The important, universal factors limiting the processing ability and information storage of these brains are the following. These limits are derived from physical arguments and upper limits on what we know about atoms, degenerate matter, and quantum mechanics. We make NO other sets of assumptions – such as what exactly this brain is made of, how it operates, etc.

1. **Processing and information density** – limited by materials used and the sizes of individual components or by laws of physics.
   a. Normal matter (~1 gm/cm^3 density) – $\mathbf{10^{21}}$ **bits/cm^3** for a "diamondoid" substance.
   b. Degenerate (white dwarf) matter – $\mathbf{10^{30}}$ **bits/cm^3**.
   c. Degenerate (neutron star) matter, or quark-gluon plasmas, or some "weird" condensates (details can be found in the paper and references therein) – $\mathbf{10^{40}}$ **bits/cm^3**.
2. **Processing speed** – limited by, again, the time scale for natural processes[4].
   a. Molecular devices (may include organic or semiconductor or "diamondoid"), which are limited by energy to break up bonds – $\mathbf{10^{-15}}$ **seconds**.
   b. Nuclear matter devices (in degenerate matter) are limited by the time scale of nuclear reactions – $\mathbf{10^{-24}}$ **seconds** or slower.
   c. Planck time on time scales at which quantum gravity becomes important, essentially where time becomes "grainy" – $\mathbf{10^{-43}}$ **seconds** or slower.
3. **Communication delays** – arising from size and placing an upper limit on computational speed.
   a. Either the brain needs to be small, to minimize the delays between disparate parts of the brain.
   b. Distributed, heierarchical computation – our brain is a rudimentary example of this. That is, the single

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[3] Taken from "The Physics of Information Processing Superobjects: Daily Life Among the Jupiter Brains," by Anders Sandberg (1999).
[4] Can be used in determining the energy of a specific computation, and using the Heisenberg uncertainty principle to calculate the time scales.

superbrain might consist of separate regions which are largely self-contained (on say, time scales of individual components) which then interact with larger regions, which then interact with other regions.

   c. Maybe disjointed brain – independent compartments that interact with each other only rarely?
   d. Combos of the above?

4. **Energy supply** – remember, energy is required for all of these computations to occur, and determined by the energy source.
   a. **Can be a star** – simplest thing we know of.
   b. **Radiation from black holes** – again, this may be collected by a similar Dyson sphere, this time surrounding a mini black hole.
   c. **Other, more exotic sources of material**.
   d. **Recall, the minimal energy required for performing a calculation is** $E_{\min} = k_B T$.

Sizes and Communication Delays of the Matrioshka Brains Themselves

- Upper limits on solid materials placed by the limiting pressure at which a material breaks down – for a “diamondoid” brain, this is 10000 km. **An easy way to calculate this is the limit at which the pressure equals the binding energy density of the material at the core**.
- Absolute limit – the minimum size at which something becomes a black hole, or the Schwarzchild radius:

  $$R_S = 2GM / c^2$$

  Where G = 6.673 x 10^{-11} kg^{-1} m^3 s^{-2} is gravitational constant, M is the mass of the object, and c = 3 x 10^8 m/s is lightspeed.

A good measure is the “coherence” of a given computer. This factor is described as:

$$S = \frac{(size)}{(time)(velocity)}$$

- (size) – refers to the maximum dimensions of the system.
- (time) – the time to perform one calculation.
- (velocity) – velocity of signal propagation – cannot be faster than lightspeed.

For human brain: (size) = 10 cm, (time) = 10^{-3} seconds, (velocity) = 100 m/second, so S = 1.

- High S – means the system is “incoherent,” in that we have asynchronous processing (“the left hand does not know what the right hand is doing”)

- Low S – coherent system, such as in computer chips, so that computer acts as one element.

Matrioshka brains, if they are Dyson spheres or anything larger than mini black holes, suffer from high incoherence – **thus, perhaps heierarchical processing (as in human brain)**.

Absolute Bandwidth Limits

The different parts of the brain need to communicate with each other, since these brains are "incoherent" (have a very high S >> 1).

No intrinsic reason to communicate in radio. The bandwidth of signal propagation is given by the frequency of propagation.

- Radio propagation, frequency ~ 10^9 Hz, so 10^9 bits/second from radio. Visible has higher frequency, hence higher transmission rates.
- Possible limits based on the production of electron-positron pairs from the light used – something like 10^{29} – 10^{30} bits/second?
- Quantum limits on propagating information through photons[5] -- **BW = 2.03 x 10^{17} (P/1 W)$^{1/2}$ bits/second**, where P is the power output of the transmitter.
- The Planck bandwidth limit, transmission rate of 10^{43} bits/second (probably very little transmission from photons for reasonable (?) detectors).

The noise power level received by any detector is given by $P_{noise} \sim k_B T_{Noise} BW$, where T_{Noise} is the noise temperature of the detector and BW is the bandwidth. Thus, lower bandwidth means the signal-to-noise is higher (b/c less noise b/c smaller number of "bins").

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[5] C. Caves and P. Drummond, "Quantum Limits on the Propagation of Bosonic Communication Rates," *Reviews of Modern Physics* **66**, 481-537 (1994).

THE BEKENSTEIN LIMIT ON INFORMATION AND PROCESSING[6]

Using arguments explained in this book[7] -- using the Heisenberg uncertainty principle and without using quantum field theory – the maximum allowable information stored in object with mass M and size D is

$$I_{Bekenstein} = 2.58\times10^{43}\left(\frac{M}{1\,\text{kg}}\right)\left(\frac{D}{1\,\text{m}}\right)\text{bits}$$

Furthermore, the maximum possible information processing rate (and hence bandwidth) is given by

$$BW_{Bekenstein} = 7.74\times10^{51}\left(\frac{M}{1\,\text{kg}}\right)\text{bits/second}$$

Matter cannot be concentrated too closely, otherwise it will collapse into a black hole. Thus, the maximal possible information density (above that of even the Planck density), is given by, in terms of mass M:

$$\rho_{Bekenstein} = 2.801\times10^{90}\left(\frac{M}{1\,\text{kg}}\right)^{-1}\text{bits/cm}^3$$

For the smallest masses, the Planck mass $M_{Planck} = 5.5\times10^{-8}$ kilograms, this places an absolute upper limit on information density and lower limit on bandwidth:

$$\rho^{Planck}_{Bekenstein} = 5.09\times10^{97}\ \text{bits/cm}^3$$
$$BW^{Planck}_{Bekenstein} = 4.257\times10^{44}\ \text{bits/second}$$

This is, supposedly, the "Planck information density" beyond which no additional information could be encoded.

Likewise, there is significant information (44 bits) in a single hydrogen atom!

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[6] Taken from J. Bekenstein, *Physical Review D* **23**, 287 (1981).
[7] F. Tipler, *The Physics of Immortality*. Macmillan, London, 1984.