Excursions in Computing Science:
Book 8d. Rocket Science.
Part III The Space Adventure.

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September 19, 2024

I. Prefatory Notes

28. Economics.

Space projects are intrinsically big and we won't do them until we can afford them.

To explore what needs to be done without getting into technology forecasts we might stick with economics. We can ask *when* we expect to be able to launch any particular expedition or probe.

Project	Objective	Mass	Energy	/Saturn V	Doublings	Year
Saturn V	Apollo Luna	2.2KT×4TJ=10.9TJ		1	0	1970
Kuiper Belt	40 A.U.	1T	1TJ+18TJ	1.7	0.8	1986
Heliopause	121 A.U.	1T	1TJ+163TJ	15	3.9	2058
Solar Gravity Lens	550 A.U.	1T	3.42PJ	314	8.29	2140
Oort Cloud	2000 A.U.	1T	45.2PJ	4150	12	2210
Oort Cloud	10,000 A.U.	1T	1.13XJ	10.4K	13.3	2240
Firefly	Proxima Centauri	2.2MT	158.4XJ	14.5M	23.8	2450
Avalon	space colony	62.49MT	176.2XJ	16.6M	23.9	2450

The first six columns of the table are relatively straightforward. We can calculate the energy required to reach any of the destinations in acceptable time. We can compare that with the energy of a past major project, the Apollo launches around 1970. And, preparing for the last step, we can work out how many doublings these factors represent: 16× is 4 doublings, 1000× is 10 doublings, and so on.

Here are the projects in brief, and the energy calculations I did,

Saturn V is the rocket used for the manned Apollo missions to the Moon. I use the energy for a single launch by taking the total mass of fuel (the sum of differences of empty from full masses of each of the three stages) and considering it to be comparable to TNT, a kiloton of which produces 4 terajoules of energy.

The Kuiper Belt is a super asteroid belt reaching from the orbit of Neptune at 30 A.U. (an astronomical unit is 150Gm) to 50 A.U. Like the asteroid belt it could be a source of raw materials extractable by robots (or miners) without the energy costs of lifting the extracts out of deep gravity wells.
For this and the next four projects I consider the energy requirements to take a 1-tonne probe to its destination in a year. This requires overcoming a potential-energy difference of

$$GM_{\text{Sun}}m\left(\frac{1}{r_{\text{Earth}}} - \frac{1}{r_{\text{destination}}}\right) \approx 1 \text{ TJ}$$

(I've counted $r_{\text{destination}} \approx \infty$ for all five destinations) and kinetic energy

$$\frac{mv^2}{2}$$

multiplying from velocity v of 1 A.U./year = 4.75 Km/sec.
Doubling the velocity or quadrupling the mass will quadruple the energy needs, adding two doublings to the final comparison.

The Heliopause is the distance from the Sun at which the solar wind meets a correspoding interstellar wind. It is sort of a bow-wave for the Sun's motion through space. It was crossed by Voyager 1 on Aug. 25, 2012, thirty-five years after launch, moving at 3.4 A.U./year.

The Solar Gravity Lens focus, from 542 A.U., is where light rays from distant stars and bent by the Sun's gravity (according to general relativity) meet, providing tremendous magnification and hence a prime location for an observatory of exoplanets (among other things).

The Oort Cloud bounds our solar system from interstellar space, and is another collection of bodies smaller than planets, but forming a sphere around the Sun, unlike the asteroid and Kuiper belts.

Firefly is the proposed fusion rocket discussed in Note 7 of Part I. I calculated its kinetic energy based on mass and a speed of 4% of lightspeed.

Avalon is a proposed space colony, discussed in Notes 29, 30 and 33. It was designed as an Earth-Moon trojan, i.e., to occupy one of the Earth-Moon L4, L5 Lagrange points, so I calculated the potential energy of lifting all its material from the lunar surface.
Given that this energy need is about the same as that of the star probe, but that such a colony would probably be needed, well prior to such a probe, to develop the economy of the solar system by mining the asteroids, it would be better designed to occupy, say, a Jupiter trojan point and be assembled, less expensively, from the asteroids themselves, away from any deep potential-energy well.

So we have the energy requirements for various stages of exploring the solar system, leading to a fusion-powered probe to Proxima Centauri, our nearest interstellar neighbour.

How do we use this to forecast when these stages might be feasible?

Here we get a little more tentative. We suppose there is a correlation between energy and money, specifically between the energy consumed by society and its gross domestic product, GDP.

A Saturn V launch in 1970 cost 185M$. The U.S. GDP was then 1.073T$, 5800 times that.

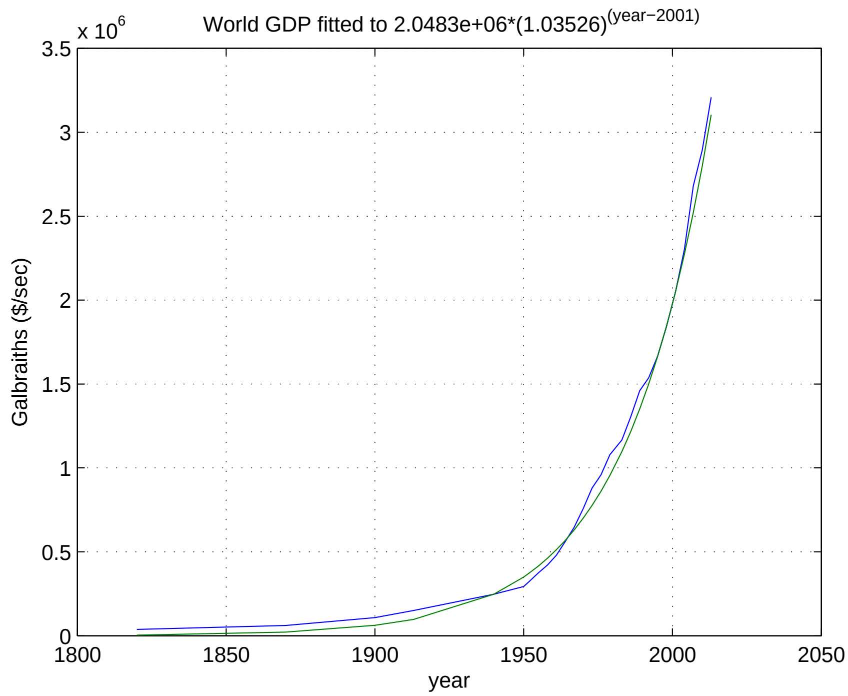
The Apollo program to put a person on the Moon, of which the Saturn launches were a part, had its largest budget, 1.2G$, in 1966, when the U.S. GDP was 813G$, 680 times that. So the Apollo project cost up to 0.15% of GDP. (The budget of NASA, the National Aeronautics and Space Administration, which sponsored Apollo was, that year, 4.5G$, or 0.55% of GDP.)

If we suppose that similar ratios of cost to GDP will be politically acceptable for projects such as Firefly, then we can use the energy ratios in the above table to project what the GDP will have to be to support the projects.

Finally we must extrapolate GDP into the future to see when such levels of the economy might be expected. Extrapolating is highly risky, but here we go.

The world GDP to present seems to fit a pattern of doubling every twenty years[1].

[1] To relate doubling period to growth rate as percent interest, divide one into 72 to get the other. Thus 72/20 = 3.6 which is almost the percentage increase I used in the plot. This works for small interest and long doubling periods. For the mathematically inclined, it follows from $e^{0.72} \approx 2$. (The 72 could be improved, but it is handily divisible by several small numbers.)

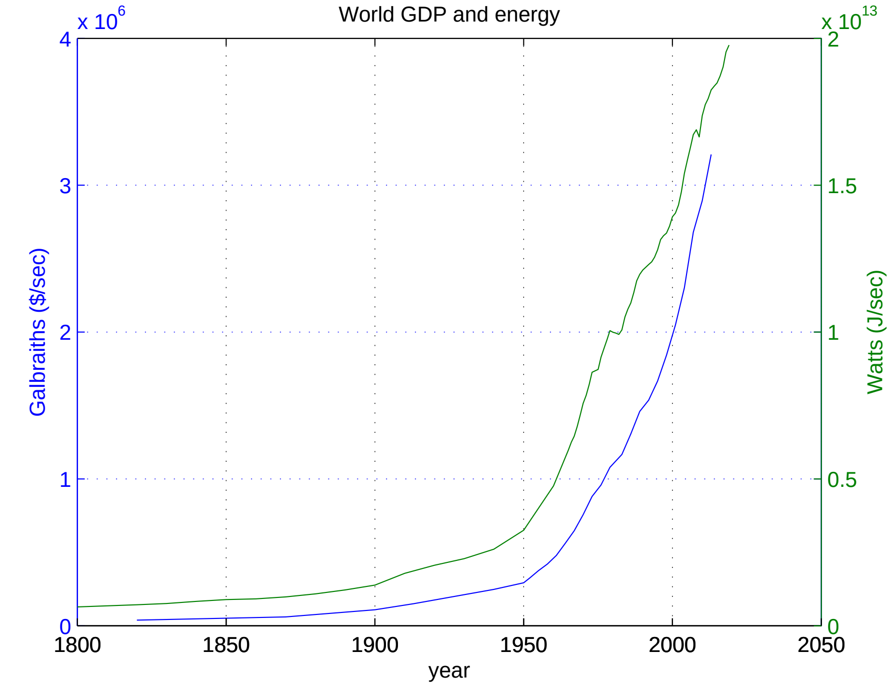


If this holds for the next few centuries, we must just multiply the numbers of doublings in the above table by 20 to get the number of years we must work through from 1970, and hence a forecast date for each project.

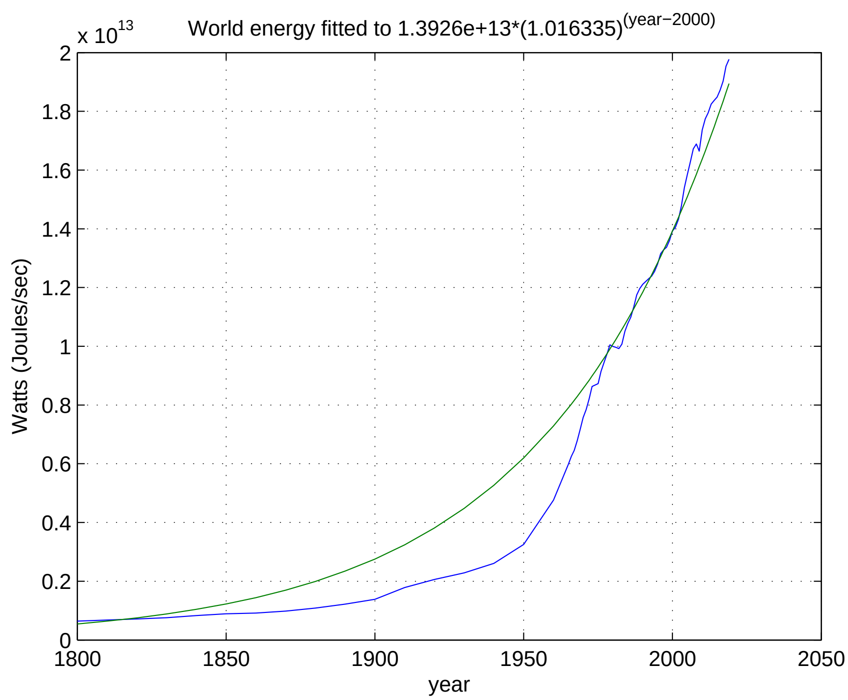
I will not try to answer the question, Are 20-year doublings sustainable for centuries? But clearly they are not if we are restricted to the planet Earth. We will have to expand the global economy off-planet, to the Moon and Mars and particularly the asteroids. The above stages, moving progressively outward in the solar system, are meant to indicate such expansion.

The other question is, Can energy serve as money? The answer is, so far, at best, Sort of. (It might be very nice to have an "energy standard" for currency, with the stability of a gold standard but not the arbitrariness of the value of gold.)

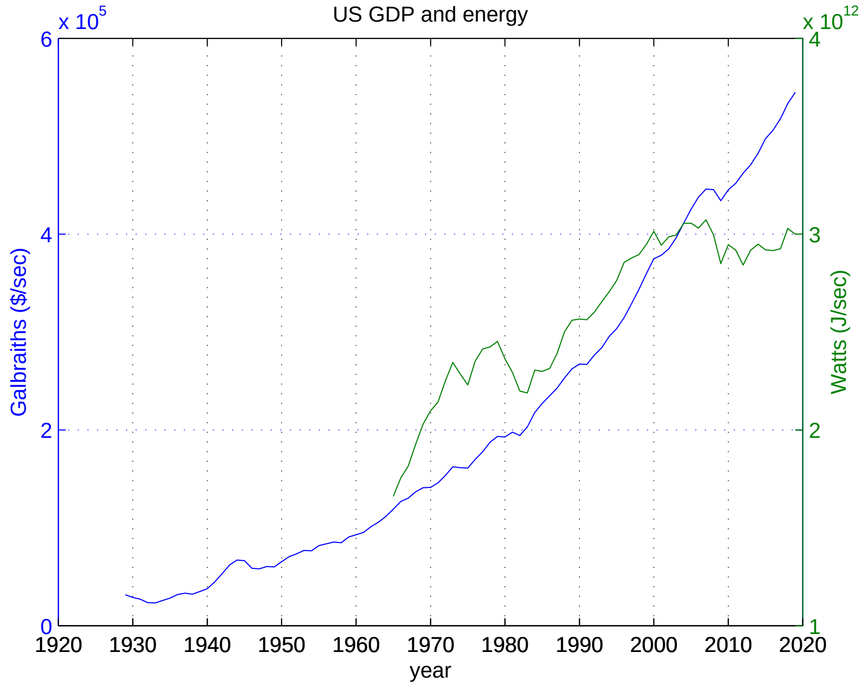
Here are world GDP and world energy consumption plotted together. The two curves sort of parallel each other, with a conversion factor of 160$ per gigajoule. I've plotted *rates*, watts for energy (joules per second) and Galbraiths for GDP (dollars per second, instead of teradollars per year, the usual measure). That way the same numbers compare joules to dollars.



But, while we had GDP doubling every 20 years, a 40-year doubling gives a better fit to the energy curve. So if we took that, we'd have to double all the above time estimates.



Also we don't always get a smooth correlation. Here is the comparison for the USA.



There is a middle section, from the mid-80s to 2000, which correlates pretty well, but are the other parts anomalous? Vietnam war? Offshore manufacturing and a transition to a service economy?

Nikolai Kardashev proposed a scale of technological culture in which Type I uses all the solar energy incident on the planet, Type II uses all the energy of its star, and Type III uses all the energy of all the stars in its galaxy. According to the extrapolations of this Note, we will achieve Type I status (167Pw) in 260 years, and Type II status (0.4Yw) in 680 years.

29. Microgravity. Every adventure has its hazards. The first hazard of human space travel is weightlessness.

When you are in orbit you are effectively falling around the Earth. Being round, the Earth curves away from you as fast as you fall, so you go on falling indefinitely. Most astronauts get over the feeling that "everything's floating inside", and the dizziness of turning their heads suddenly, in a few days. Some are nauseated all over again when they return to normal gravity.

Longer-term effects include bone loss, at ten times the rate of osteoporosis, mitigated by a couple of hours of daily exercise, and usually recovered by three or four years after landing; and unexplained changes to the eyes called "spaceflight-associated neuro-ocular syndrome" (SANS). Scott Kelly, who was in space for 7, 15, 134 and 340 days, and who participated in a medical comparison study, with his astronaut twin brother back on Earth during the last flight, said "I couldn't imagine coming back to Earth after being in space for many years."

We cannot generate gravity, but we can use centrifugal force to mimic it. (See Note 11 of Part II.) The solution is to spin the spacecraft.

Using the angular velocity ω (see Note 26 of Part II) the centrifugal acceleration is

$$a = \omega^2 r$$

where r is the radius of the spinning (part of the) spacecraft.

We would like this acceleration to equal 9.8 meters/sec^2 or one gee, the acceleration due to gravity at the surface of the Earth. Or equal to some fraction f of it: for instance, gravity on the Moon is

1/6 gee and gravity on Mars is 1/3 gee (well, 38%).

There is a problem with living, or more specifically moving, on a spinning cylinder. The other rotational "pseudoforce", the Coriolis force (see Note 27 of Part II), will rotate the fluid in the semicircular canals of our ears, which help us keep our balance, any time we move in the same (or opposite) direction as the motion of the spin. If the angular velocity is too great we will get dizzy.

So let's keep the angular velocity down to 2 or 3 revolutions per minute, that is

$$\omega < \frac{2\pi}{30} = 0.2 \text{ radians/sec}$$

Then, for 1 gee, the radius of the spacecraft must be

$$r > \frac{g}{\omega^2} = \frac{9.8}{0.2^2} = 250 \text{ meters}$$

This is pretty big for a spacecraft. If we choose to live with less "gravity" we can reduce this radius by the corresponding fraction, but simulating even lunar gravity would require a radius of over 40 meters.

So the solution of centrifugal force may be more appropriate for a space habitat such as Avalon (mentioned in Note 28 and discussed in Notes 30 and 33), which proposes a radius of 530 meters and would spin at 1.3 rpm for 1 gee.

A space habitat for mining the asteroids, or a cycler (see Note 22 of Part II), or a worldship taking generations to reach the stars, all could be large cylinders, spinning for artificial gravity. But note that they cannot be too long for their radius, or they will tumble rather than spin.

The reason is that cylinders have different moments of inertia (see Note 26 of Part II) in different directions. A cylinder of radius R and length L has a moment of inertia along its long axis of $I_1 = MR^2/2$ but moments of inertia along the other two perpendicular directions of $I_2 = MR^2/4 + ML^2/12$. These are equal when $R^2 = L^2/3$, i.e., $L = R\sqrt{3} \approx 1.7R$.

For the same angular momentum $I_1\omega_1 = I_2\omega_2$, or $\omega_2 = \omega_1(I_1/I_2)$, rotation about the second axis (tumbling) takes less energy, $I_2\omega_2^2/2 = (I_1/I_2)I_1\omega_1^2/2$ than rotation about the first (spinning) when $I_2 > I_1$.

So L must not exceed $1.7R$. Avalon has $L = 680$ meters, which is 1.28×530. Oumuamua, the first interstellar visitor we have discovered (at the Haleakala Observatory in Hawai'i in 2017) is 400 meters long with $L/R \approx 10$, and tumbles end-over-end with a period of 7.3 hours.

The other apparent solution to the microgravity hazard would be constant acceleration while travelling, as might be provided by fusion propulsion.

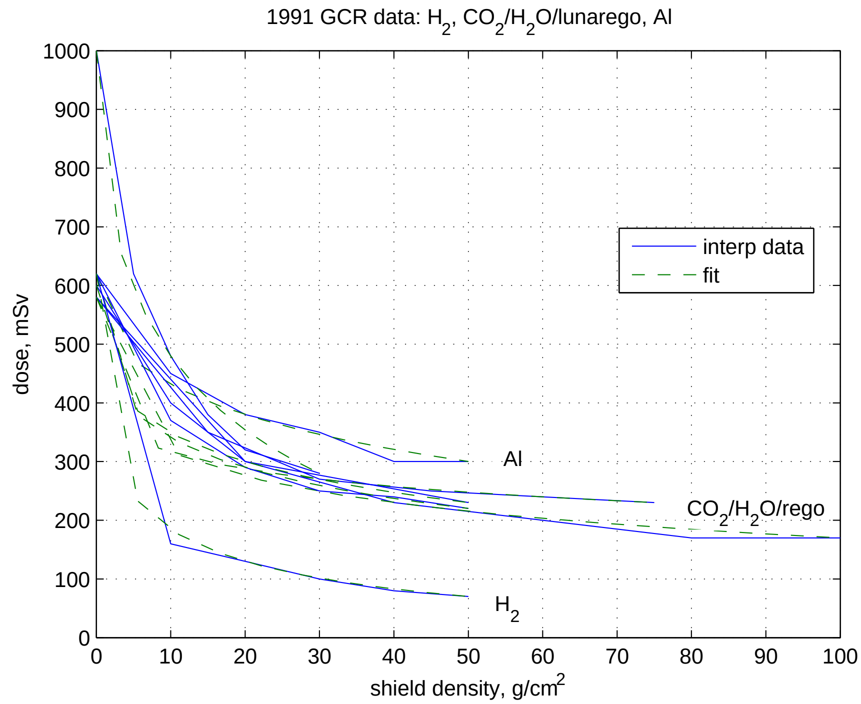
30. Radiation. A worse hazard to space travellers is radiation. Solar flares add immensely to the charged particles, mainly protons, which we've already seen in a minor but useful way in the solar wind. And there is a constant background of high-energy galactic "cosmic rays", originating in supernovae (and some really energetic ones occasionally from outside the galaxy—which may even offer a challenge to the theory of special relativity).

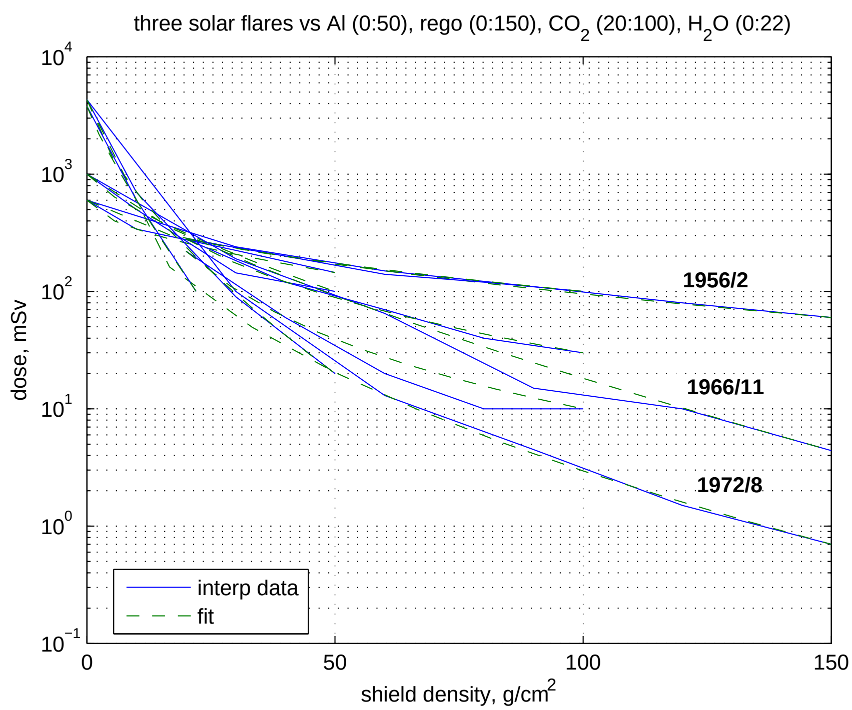
On Earth we are protected by the atmosphere and especially by the Earth's magnetic field. Space vehicles, the Moon and Mars have no magnetic field, and of these only Mars has an atmosphere, albeit thin, mainly CO_2.

So we need shielding. It can be the aluminum (Al) skin of the spacecraft, "regolith"—the surface material of the Moon or Mars,—or other substances. Materials with a lot of hydrogen—polyethylene (PE), lithium hydride (LiH), water (H_2O) or, best of all, liquid hydrogen (LH)—are good because solar and cosmic protons are slowed most effectively by hydrogen nuclei, themselves protons (see the discussion of collisions in Note 17 of Part II).

Here are graphs showing how well various materials stop galactic cosmic rays (GCR) and three illustrative strong solar flares (Feb 1956, Nov 1966 and Aug 1972). (Data source: L.G.Simonsen,J.E.Nealy

1991 NASA Tech.Paper 3079)





The horizontal axes of these plots indicate the thickness of the shields. They are in grams per square centimeter—an *areal density*—so that different materials of different actual densities (grams per cubic centimeter) can be compared. (Dividing by the actual density

material	Al	CO_2	rego	H_2O	PE	H_2
density (g/cm^3)	2.7	-	1.5	1	0.97	0.07

gives the thickness in centimeters: (g/cm^2)/(g/cm^3) = cm. Note that 1.5 is only a rough approximation for regolith, whose density varies—but lunar and martian regoliths are comparable in density and in radiation protection. Note also that the density of CO_2 in the martian atmosphere varies from, say, 2_{10}–6 g/cm^3 at the surface to 0 at the top of the atmosphere.)

The shielding capabilities group into three main categories, with aluminum requiring the greatest mass, liquid hydrogen the least, and the others in between. These categories are less clear in the flares data, with regolith (the lines ending at 150 g/cm^2) looking better than CO_2 (the lines ending at 100 g/cm^2).

Note that the flares data are plotted on a semilogarithmic graph because of the extreme variations of dosage, from 4000 down to 0.7.

(I have tried, with limited success, to fit these data to exponential curves, in order to get a feel for how they behave. They do not fit the form

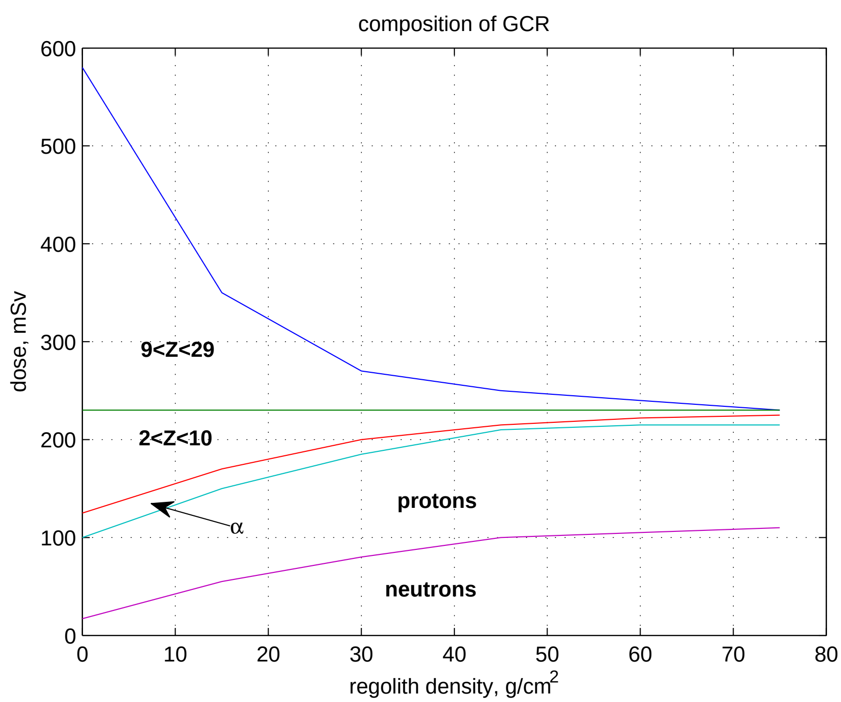
$$m \exp(-x/p)$$

for some initial magnitude m and decay rate p, as one might expect, but need the additional parameter $q < 1$ in

$$m \exp(-x^q/p)$$

We can see this in the semilog plot where the lines are concave-up instead of straight.)

The main variation in the flares data is also the difference from the GCR data and is due to the types of radiation. These vary among flares and between flares and cosmic rays. Here is an estimate of the types of radiation making up GCRs and how it is affected by regolith shielding.



The composition of the cosmic rays is shown at 0 g/cm^2. The dose is mainly caused by heavy ions of atomic number ≥ 10, followed by lighter ions (heavier than alpha-particles), followed by protons. (This ranking is not of the number of particles but of the damage they do: heavy ions are much more biologically destructive than protons or neutrons; but they also filter out faster.)

At higher thicknesses we see what happens in the regolith. Note in particular that the protons and neutrons grow in number: this is secondary radiation induced by the incident cosmic rays. Only the top curve, the total radiation, fits an $m\exp(-x^q/p)$ curve.

So far I have not discussed the vertical, "dose", units of these plots. This is given in millisieverts, mSv. A *sievert* of radiation is an assessment of the amount and type of radiation that "carries with it a 5.5% chance of eventually developing fatal cancer" [Wikipedia 21/2/11] based on a considerable amount of radiation biology which we cannot go into here.

The sievert is based on the *gray* which is the simple physical measure of how many joules are generated by the radiation per kilogram of absorbing matter, be it inert shielding or biological tissue.

The sievert is also measured in joules per kilogram but is multiplied by *quality factors* indicated by the type of radiation and the type of tissue. Here's a sketch from ICRP, the International Commission on Radiological Protection [via Wikipedia].

First, quality factors, W_r for different types of radiation.

radiation, r	energy	W_r
X-rays, γ-rays, β particles, muons		1
neutrons	<1 MeV	$2.5+18.2exp(-(ln(E))^2/6)$
	1–50 MeV	$5.0+17.0exp(-(ln(2E))^2/6)$
	>50 MeV	$2.5+3.25exp(-(ln(0.04E))^2/6)$
protons, charged pions		2
alpha particles, nuclear fission products heavy nuclei		20

Next, the percentage weights for different types of biological tissue (IRCP report 103).

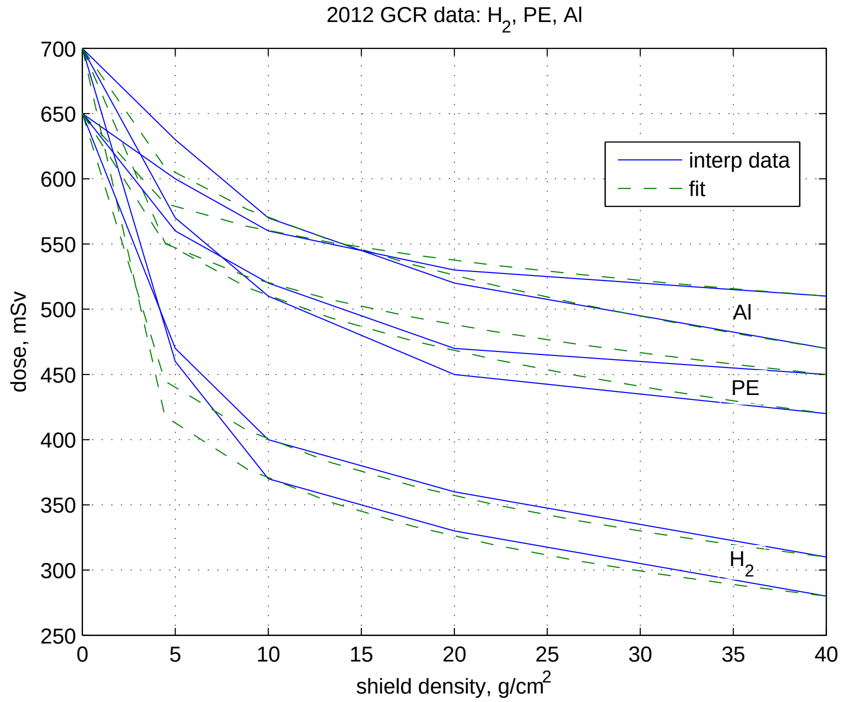
weight	#	tissue types
12	6	red bone marrow, colon, lung, stomach, breast, rest of body
8	1	gonads
4	4	bladder, liver, oesophagus, thyroid
1	4	skin, bone surface, salivary glands, brain

"The absorbed dose is first corrected for the radiation type to give the equivalent dose, and then corrected for the tissue receiving the radiation", giving effective dose.

The first category of tissue type, above, is clearly the sensitive one. The dosages in all the graphs above are cited for "BFO": blood-forming organs.

The older units for radiation, the *rad* and the *rem* (for "Röntgen equivalent man") are 1/100 of the gray and the sievert, respectively. You can think of them as the cents in the dollars-and-cents measures of radiation, e.g., 1.2 Sv = 1 Sv, 20 rem, but the different units are not in fact mixed this way. The doses recorded in the plots above are from a 1991 paper and given originally in rem. I multiplied by 10 to get millisieverts. (I could have multiplied the areal densities also by 10 to get kg/m^2 instead of the non-MKS g/cm^2, but the latter has been used throughout so I've kept it.)

Something else seems to have changed with the change of units. Here are dose vs shielding plots for GCR from a 2012 paper, presented there in mSv. Compare with the first plot above. The biology now seems more sensitive. I should note that all the data I've presented was calculated by their authors from computer models rather than measured by exposing the substances to cosmic rays or solar flares; the models have surely changed. (Data source: F.A.Cucinota et al., NASA TH-2012-217361.)



That's 21 years later. What has happened since?

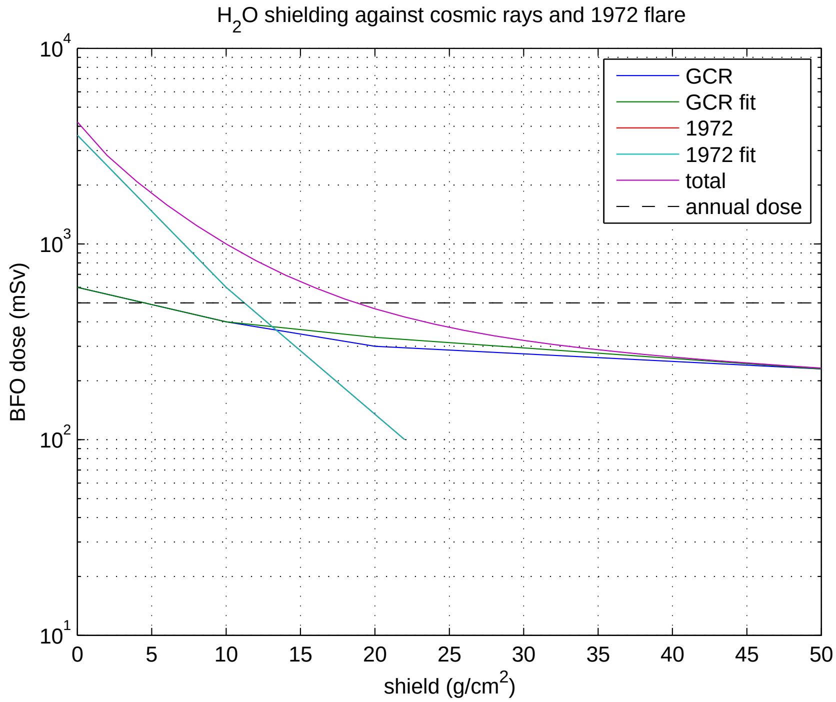
We must ultimately use this science to design safe spacecraft and habitats. So we need to know what dosage is acceptable. Here are dose limits adopted by NASA for US astronauts. (I've converted from rem to sievert.)

	skin	blood forming organ	eye
30-day	1.5	0.25	1.0
annual	3.0	0.5	2.0
career	6.0	1.0–4.0*	4.0

*Depends on age and gender.

Since the blood forming organs (BFO) are the most sensitive, we take the middle column as the limit.

The 1991 analysis proposed that the sum of the annual galactic cosmic radiation and one serious solar flare would provide a reasonable estimate of the annual radiation hazard for a spacecraft or a habitat. Here's the plot, in millisieverts, showing also the annual limit of 500 mSv for BFO.



For their further proposals for spacecraft and habitat design, see the Excursion for this Note.

The Avalon colony mentioned in Notes 28, 29 and 33 is protected from radiation and micrometeorites by an outer shield of anhydrous glass, which could be made from silicates that are waste from processing asteroids for metals. The authors propose a thickness of 340 cm, which, at a density of 2 g/cm^3 (silicon dioxide is the main component), is an areal density of 680 g/cm^2—way off the scales of the plots we've discussed above, if the radiation protection is anything comparable to the materials we've seen.

That outer hull of Avalon *counter*-rotates in such a way as to offset the angular momentum of the inner hull, which is rotating for artificial gravity. Thus Avalon has zero net angular momentum and can be turned to face the Sun for light and heat continuously in the course of its orbit. (That is, it has the slight angular momentum for this turning, perpendicular to the axis of those two rotations.)

31. Space debris. Every technology has its bright side and its dark side. It is worth coining words, to keep us alert to both possibilities: eutech and dystech. The eutech of the automobile is personal mobility; the dystech is traffic jams (anybody think flying cars are a good idea?). The eutech of the Internet is communication and wide access to knowledge; the dystech is viruses and rapid dissemination of untruth. The eutech of rocket science is to boldly split an infinitive, sorry, "to boldly go ..."; the dystech, for the moment, is space debris.

Dr Holger Krag, Head of the European Space Agency's Space Debris Office, put the problem graphically in his guest editorial to the Journal of the British Interplanetary Society's issue from the 7$^{\text{th}}$ European Conference on Space Debris (Vol.70 No.2/3/4 2017):

> Since 1957, more than 5,250 space launches have led to an on-orbit population today of more than 23,000 tracked debris objects. Only about 1,200 are functional spacecraft. The remaining are classified as space debris and no longer serve any useful purpose. A large percentage of the routinely tracked objects are fragments from the approximately 290 breakups, explosions and collisions of satellites or rocket bodies that are known to have occurred. An estimated 750,000 objects larger than 1 cm and a staggering 166

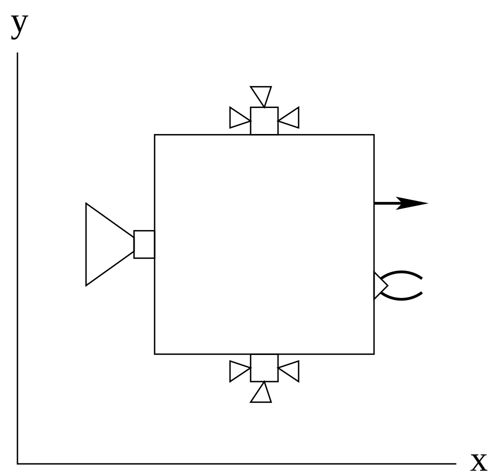
million objects larger than 1 mm are thought to reside in commercially and scientifically valuable Earth orbits.

On the next page of the issue is a scary image of Earth barely visible through the debris, 70% of which are in LEO, low Earth orbits, up to 2000Km above the surface.

As well as all the small stuff, there are also large objects, which should be removed before they explode or get broken into unmanageable pieces by collisions. An example is the European Space Agency's ENVISAT, at 8 tonnes, launched in 2002 into a crowded polar orbit at 800 km, which ceased functioning ten years later.

To remove debris from orbit we must slow its velocity enough to switch it into a transfer ellipse which does not take it to a lower orbit but forces it into the Earth's atmosphere, where it burns up on re-entry. (The International Space Station does that periodically with garbage it cannot recycle on board.) For large derelicts the trajectory must avoid most of the space above the Earth, in case large parts fail to burn up and land on populated ground.

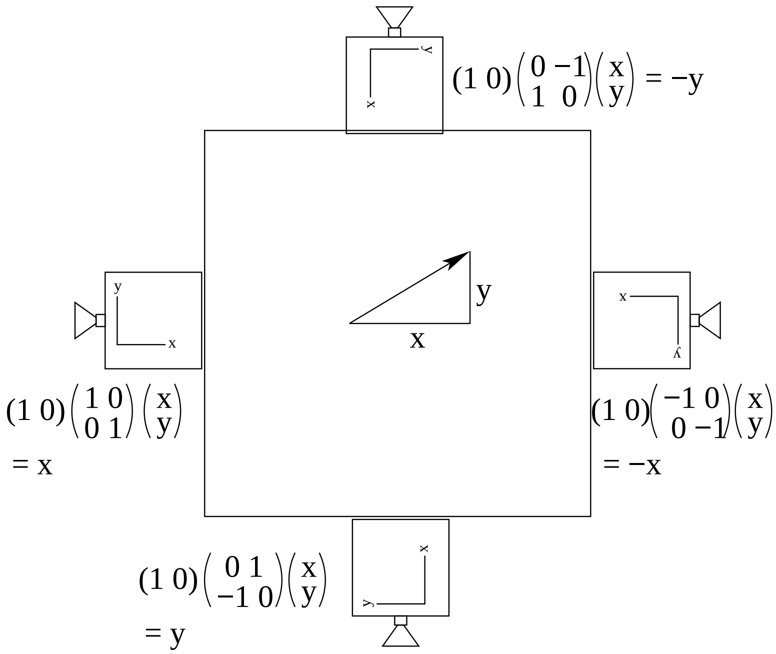
For a large derelict a special mission to de-orbit it is worthwhile—one for ENVISAT is still being planned. I'd like to consider an approach which might work for all space debris: a cooperative swarm of "tractor" spacecraft.



thrust = (1,0)

Here is a schematic of one unit. It has a main thruster (on the left), small maneuvering jets (top and bottom), and attachment devices (on the right) such as a harpoon or a gripper. It has its own x-y coordinate system, with main thrust in the x-direction. This is indicated above by the "vector" $(1, 0)$ which gives a direction in which x is 1 while y is 0.

To deal with something big, several tractors must cooperate. Let's look at a cubical derelict (well, square in two dimensions). Here are four tractors attached to it, one on each side.



The tractors are rotated to fasten on to their respective sides. To move everything in the direction $\begin{pmatrix} x \\ y \end{pmatrix}$ shown by the arrow—that is for every x meters we move from left to right we also move y meters upwards—the tractors must figure out how strongly to fire their thrusters.

Obviously the tractor on the left will thrust proportional to x and the tractor on the bottom will thrust proportional to y. The other two can turn their thrusters off.

In the diagram I've told each tractor how to figure out its thrust, using the "matrix" product

$$(1,0)\begin{pmatrix} c & s \\ -s & c \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}$$

The $(1,0)$ is just the thrust vector for each tractor as given in the figure before. The last matrix is the x-y direction we want everything to move in.

That leaves the middle matrix, of four numbers. What I've called c and s take on only the values -1, 0 or 1 as shown in the figure. If we know how to do matrix multiplication, the matrix triplets multiply out to give x, y, $-x$ and $-y$, respectively, as shown in the diagram. (A negative result must be interpreted to mean no thrust.)

When c and s are other numbers (restricted to $c^2 + s^2 = 1$), that middle matrix describes any rotation of the tractor, so that the math will work not just for square derelicts.

Furthermore, I've shown the tractors set up so their thrust is through the center of mass of the assemblage, which thus does not spin (rotate) under thrust. More generally, rotation must be compensated. Indeed, the derelict was probably rotating on encounter and that rotation should be stopped.

But we won't go into the full story.

With "swarm intelligence" the tractors can cooperate as equals, without a hierarchy of command. This simplifies the mission and allows for failure of individual tractors, as long as there are some spares to replace them. (A derelict tractor will have to be de-orbited, too, and so they should be designed with handles to attach to.)

I can sketch out how a swarm of tractors can move through space, say on their way to a target, but not go into cooperating to remove the target.

If we ask how a flock of birds, or a school of fish, moves in a coordinated way, we come up with three simple rules. (And, to avoid specific zoology, we call the individuals “boids”.)

1. Stick together
   (a) in position;
   (b) in speed.
2. Avoid collisions.

These rules each leave a quantity unspecified, and, if we write a computer program to try them out, we must experiment with numbers.

Each boid is represented by its position, x, y and, for three dimensions, z, and by its velocity, v_x, v_y and, ditto, v_z. (I'll stick to two dimensions.)

The first two rules can be implemented by accelerating each boid towards the average of all the others (or of a “local” subset of all the others). That is, we add to the boid's velocity small multiples of the differences of a) its position and the mean and b) its velocity and the mean.

The third rule also adds a small velocity to each boid, proportional to the inverse of the distance from other, close boids, so that the acceleration is small if they are far apart and large if they are close together.

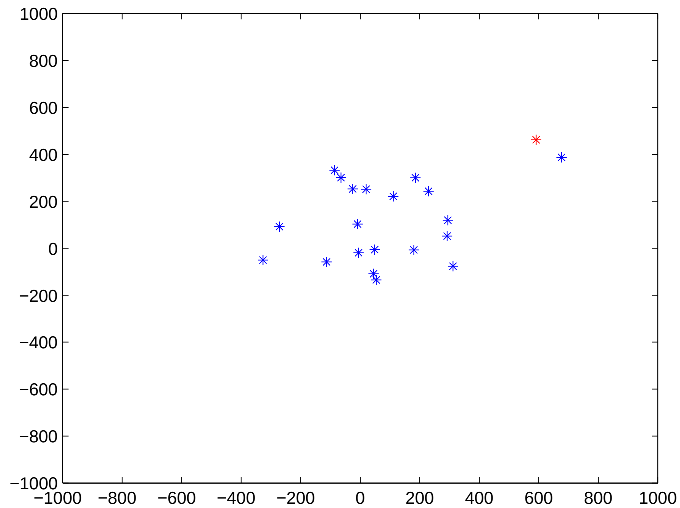
Here are the rules for the x-components. The y (and z) components are similar.

1. (a) $v_{x1a} = (x-$ average of all (or local) other $x)/p$
   (b) $v_{x1b} = (v_x-$ average of all (or local) other $v_x)/v$
2. $v_{x2} = c(v'_x - v_x)/((v'_x - v_x)^2 + (v'_y - v_y)^2)$ added up for each close boid at x', y' which has velocity v'_x, v'_y.

where p, v and c are the numbers we are trying as parameters. (And, if we go for local attractors instead of the whole swarm, we need a fourth parameter to tell us how many nearest neighbours in space count as “local”.)

That's four numbers to decide on, a big choice. My own simulation didn't do so well[2], but here is a swarm of 20 “tractors” chasing a target “derelict”.

[2]I could learn from starlings, which are famous for such flocking, called murmurations, can see 296 degrees (of which the forward 26 is binocular) and typically track about seven neighbours, according to a note by Diana Marques and Nick Dunlop in *National Geographic* (*Aerial Acrobatics*, Oct. 2021 p.26).



Something like this may enable us to de-orbit large objects, but we must change tactics to deal with all the small pieces. Unfortunately a vacuum cleaner won't work in space.

We might use nets, carried cooperatively by several members of a swarm. I don't know how to begin specifying a controller for that kind of flying, but things like it have been done for swarms of flying drones and there's a TED talk or two.

That's a beginning on clearing out existing debris. There must also be effective regulation to ensure all new satellites a) de-orbit themselves at the end of their lives (if that is predictable) and b) consume all their remaining fuel in the process to avoid explosions. And, for satellites that have failed and cannot de-orbit themselves, it would be helpful if all had a standardized "handle" for grabbing by de-orbiting spacecraft.

Space travellers cannot afford to have even very small debris coming at them at kilometers per second, on top of all the other hazards.

32. Space elevator. Enough of hazards. Let's see if we can get out of Earth's "gravity well" more cheaply than by using rockets and polluting the atmosphere. How about a cable?

Unfortunately we can't run a cable from Earth to the Moon, say: that cable would wrap itself around the Earth every 28 days. (It would not wrap itself around the Moon, however: why?) And a cable to the International Space Station would wrap around the Earth every 92 minutes and 40 seconds.

But we *could* run a cable from some spot on the Earth's equator to a geosynchronous orbit directly above it.

A *geosynchronous* orbit is a circular orbit whose period is 24 hours, so that, if it is equatorial, a satellite in that orbit appears to remain directly above a fixed spot on the equator. As for all orbits, the gravitational attraction is matched by the centrifugal force (Note 11 of Part II):

$$\frac{GM}{r_G^2} = \omega^2 r_G$$

so the radius of the geosynchronous orbit, r_G, satisfies

$$r_G^3 = \frac{GM}{\omega^2}$$

We cannot just leave the end of the cable at r_G because at all lower points on the cable its weight overrides the centrifugal force on it, and it will fall.

So the cable must extend beyond r_G, where the centrifugal force begins to dominates, far enough to counterbalance the part below. We'll call the top of the cable its *apex* and we can calculate how big r_A, the radius of that apex, must be.

As well as r_A and r_G we also need r_E the radius of the Earth's equator.

We will have to add up the (downwards) gravitational force plus the (upwards) centrifugal force on every bit of the cable from r_E to r_A. If r_A is right this sum will be zero.

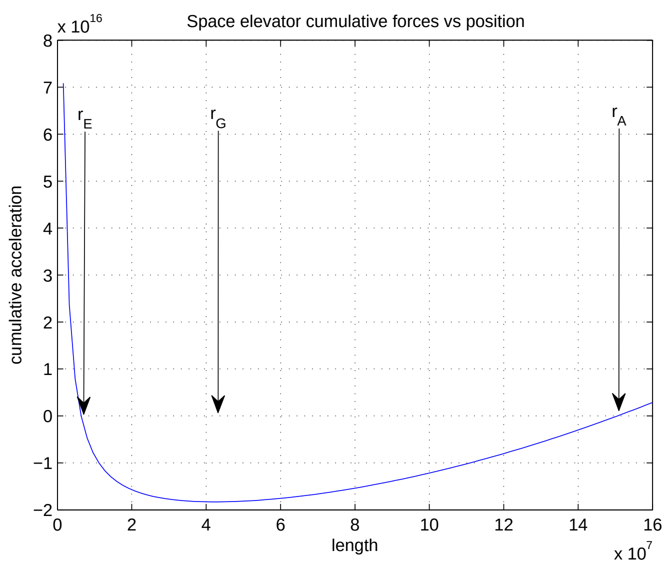
$$0 = \text{ sum } (r_E \text{ to } r_A) \text{ of } \; -\frac{GM}{r^2} + \omega^2 r$$

We could use a computer to add up all these pieces, but fortunately calculus allows us to write the answer explicitly.

$$\begin{aligned} 0 &= \left[\frac{GM}{r} + \frac{\omega^2 r^2}{2}\right]_{r_E}^{r_A} \\ &= \frac{GM}{r_A} - \frac{GM}{r_E} + \frac{\omega^2 r_A^2}{2} - \frac{\omega^2 r_E^2}{2} \\ &= \frac{\omega^2 r_G^3}{r_A} - \frac{\omega^2 r_G^3}{r_E} + \frac{\omega^2 r_A^2}{2} - \frac{\omega^2 r_E^2}{2} \end{aligned}$$

where in the last line we've been able to express all the dependence on G and M in terms of ω and r_G.

Here is what that sum looks like as a function of r, from the first line above, before applying the two "limits" of r_E and r_A.



It is zero when $r = r_E$, when there is nothing to sum, and when $r = r_A$, as intended. It also goes horizontal when $r = r_G$, because the bit of the cable at r_G has zero net force on it: the forces are just changing from net downwards (below r_G) to net upwards (above r_G).

But even though that plot shows a number for r_A, I've cheated: we haven't found that number yet.

To do so, we can divide the expression for the sum

$$\frac{\omega^2 r_G^3}{r_A} - \frac{\omega^2 r_G^3}{r_E} + \frac{\omega^2 r_A^2}{2} - \frac{\omega^2 r_E^2}{2}$$

by $\omega^2/(2r_A)$: that quantity is not zero, so whenever what is left is zero, the whole expression will be zero; and what is left is easier to work with.

$$\begin{aligned} 0 = \frac{2r_A}{\omega^2}\left(\frac{\omega^2 r_G^3}{r_A} - \frac{\omega^2 r_G^3}{r_E} + \frac{\omega^2 r_A^2}{2} - \frac{\omega^2 r_E^2}{2}\right) &= 2r_G^3 - 2\frac{r_G^3}{r_E} r_A + r_A^3 - r_E^2 r_A \\ &= r_A^3 - \left(2\frac{r_G^3}{r_E} + r_E^2\right) r_A + 2r_G^3 \end{aligned}$$

This last is just a special form of the "cubic equation" in r_A and there is a solution for it

$$r_A = \frac{r_E}{2}\left(\sqrt{1 + \left(\frac{2r_G}{r_E}\right)^3} - 1\right)$$

which you can check out by finding

$$r_A^3 = \frac{r_E^3}{8}(a^3 - 3a^2 + 3a - 1) = \frac{r_E^3}{8}((a^2+3)a - (3a^2+1))$$

(where a is just the big square root) and churning through the algebra.

So we have r_A expressed entirely in terms of $r_E = 6.4$ megameters and $r_G = 42.2$ megameters and you can check that $r_A = 150$ megameters.

The Earth is about 40 megameters in circumference, so this cable could wrap itself around the planet almost four times. It's pretty long.

We should also find out how strong it must be.

The cable will experience the most tension at the geosynchronous radius r_G. That's because everything below is being pulled down by gravity and everything above is being pulled up by centrifugal force. The two balancing forces there are the sums from r_E to r_G and from r_G to r_A of the forces we gave above.

If we do the calculations

$$\begin{aligned} \left[\frac{GM}{r} + \frac{\omega^2 r^2}{2}\right]_{r_E}^{r_G} &= \left[\frac{\omega^2 r_G^3}{r} + \frac{\omega^2 r^2}{2}\right]_{r_E}^{r_G} \\ &= \omega^2\left(\frac{r_G^3}{r_G} - \frac{r_G^3}{r_E} + \frac{r_G^2}{2} - \frac{r_E^2}{2}\right) \\ &= -48 \text{ megayuri} \end{aligned}$$

And

$$\begin{aligned} \left[\frac{GM}{r} + \frac{\omega^2 r^2}{2}\right]_{r_G}^{r_A} &= \left[\frac{\omega^2 r_G^3}{r} + \frac{\omega^2 r^2}{2}\right]_{r_G}^{r_A} \\ &= \omega^2\left(\frac{r_G^3}{r_A} - \frac{r_G^3}{r_G} + \frac{r_A^2}{2} - \frac{r_G^2}{2}\right) \\ &= 48 \text{ megayuri} \end{aligned}$$

Here I've introduced a new unit of specific tension named after Yuri Artusanov who proposed a cable instead of Tsiolkovsky's original idea of a tower (and Tsiolkovsky already has the rocket equation named after him).

A yuri is a tension, measured in force per area (newtons per meter squared), divided by the density of the material (kilograms per meter cubed). If the tension is just enough to break the material, the yuri is a measure of its strength per weight. It actually has the physical dimensions of acceleration times length—which is what we got when we did the sums above, which add up force per unit mass times the little increments of length, over all the length of the cable.

$$\frac{F/L^2}{M/L^3} = \frac{M(L/T^2)/L^2}{M/L^3} = \frac{L^2}{T^2}$$

where F is units of force (newtons), M of mass (kilograms), L of length (meters) and T of time (seconds).

The yuri has a nice interpretation. If we take the acceleration part (L/T^2) to be g, the acceleration of one gee due to gravity at the Earth's surface, then the yuri is $g\ell$ where ℓ is a length which can be interpreted as the length of itself that the cable can support without breaking under one gee.

So if we take $g = 10$ m/sec^2, the 48 Myuri above requires that 4.8 Mm of the cable won't break when hanging in one gee. That's 4800 kilometers.

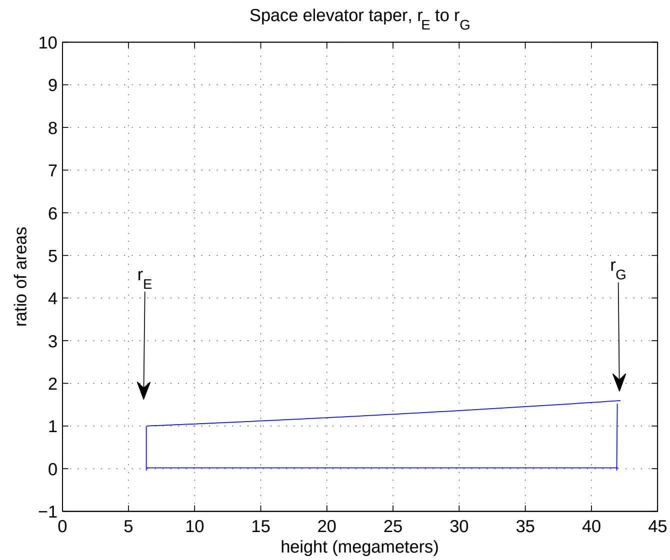
We don't have (yet) any material that strong. Here are some examples.

	tensile strength (MPa)	density (Kg/m^3)	specific strength MY = (MPa)/(Kg/m^3)
steel	5000	7900	0.63
spider silk	1100	1300	1
kevlar	3600	1440	2.5
zylon	5800	1540	3.8

(The numbers are examples: these materials have considerable variety. MPa is megapascals: a pascal is 1 Kg/m/s^2.)

Carbon nanotubes hold out a promise of strengths of ~100 MY. But they have so far been made in only microscopic lengths, a far cry from the 150Mm needed.

Good engineering would *taper* the cable so that it is under the same tensile stress everywhere along its length. This means it can be narrower at the extremes, where the total weight (near r_E) is low or the total centrifugal force (near r_A) is low. For carbon nanotubes the "taper ratio" (cross-sectional area at r_G divided by cross-sectional area at r_E (or r_A: it's the same) works out to 1.6, using calculations related to what we've done above. Here's a much out-of-scale picture of this taper, in which the areas of cross-section are represented one-dimensionally as the vertical.



The profile looks like a straight line, but it is actually an "exponential" curve, and would grow ever bigger if the parameters were different. For zylon, kevlar and steel the taper ratios are truly enormous and we would see the curves: they are really unsuitable materials.

The upper end, from r_G to r_A, is simlar.

For a tapered cable, the total length does not change from the calculation we did: 150 Mm.

However, we don't need to make the cable that long if we attach a *counterweight* to it somewhere above r_G to keep the tension.

But it should be long enough to slingshot spaceships from its far end to interesting destinations. To escape Earth's gravity, we must launch from $2^{1/3}r_G = 53$ Mm. To get to Jupiter (or to Mercury) 100 Mm will do.

We can also put stations on the cable at positions where the "gravity" is that of Mars (3.9 Mm) or Luna (8.9 Mm).

Finally, there are reasons for making the cross-sectional *shape* other than circular. A thin ribbon a few centimeters wide would provide better traction for the climbers and would help avoid space debris by running torsion waves up the cable so that it is edge-on to any tracked debris approaching it. A cable severed by an old battery or camera would be a catastrophe.

33. Ecology. Humans need Nature to survive. At the very least we need air, water and food. In space we must either imitate Nature or bring it along, perhaps much simplified.

Here is NASA's take on a person's daily needs, in kilograms per person per day.

	On Earth kg/p/d	In space kg/p/d
Oxygen	0.84	0.84
Drinking water	10	1.62
Dried food	1.77	1.77
Water for food	4	0.80

For the six-person crew of the International Space Station (ISS) that's 3.9 tonnes of dried food and 5.3 tonnes of water per year (or 5.6 tonnes of food and 3.6 tonnes of drinking water). (Water is 1 kg/litre, so 5.3 tonnes is 5300 litres.)

We also need 840 grams / 1.43 grams per litre (the density of oxygen) = 587 litres of oxygen daily. This is about 5% of inhaled air (we inhale 20% oxygen and exhale 15% oxygen plus 5% carbon dioxide), so we each need about 12,000 litres of air daily (8 liters per minute). Since only the oxygen gets consumed, we can use the oxygen figure to get 1.8 tonnes of oxygen annually for six people.

The ISS uses a non-biological Environmental Control and Life Support System (ECLSS) to recycle 93.5% of the water and 40% of the oxygen needed. This reduces imported water to 342 kg (342 litres) per year, and oxygen to 1.1 t. (NASA wants to get to 98% efficiency for a trip to Mars.)

The ECLSS on the ISS electrolyzes water into oxygen and hydrogen. It combines the hydrogen with carbon dioxide (the Sabatier process) to get water again and methane which could be used for fuel but is currently vented into space. The "CO_2 scrubbing" by Sabatier is crucial because carbon dioxide is poisonous at high concentrations.

Full recycling will probably need "bioregenerative" ECLSS. Plants complement animals such as humans by consuming CO_2 and producing O_2. They also provide food.

Here are the complementary metabolic equations, with (CH_2O) representing a unit of biomass (some of which, at least, would be food).

Humans	$(CH_2O) + O_2$	$\rightarrow$	$CO_2 + H_2O$ + metabolic energy
	clean water	$\rightarrow$	waste water
Plants	$(CH_2O) + O_2 + H_2O$	$\leftarrow$	$CO_2 + 2H_2O$ + light
	clean water	$\leftarrow$	waste water

(In the entry for Plants, the first line describes *photosynthesis* and the second line describes *transpiration.*)

We see that plants can completely regenerate the air and provide food. They also give back half the water they are supplied with.

To put some numbers to this, I'll look at experiments done with wheat. I'll pretend that all we need to eat is wheat, thus making Nature really simple. (This violates Einstein's dictum that everything should be as simple as possible, but not too simple.)

First, oxygen. How much wheat does it take to support one person breathing? A NASA experiment concluded that 11 m^2 of wheat at high light intensity will do.

Second, food. How much grain can wheat yield? Another trial involving NASA concluded "that wheat grown on a single hectare of land in a 10-layer indoor vertical facility could produce from 700±40 t/ha (measured) to a maximum of 1,940±230 t/ha (estimated) of grain annually under optimized temperature, intensive artificial light, high CO_2 levels, and a maximum attainable harvest index. Such yields would be 220 to 600 times the current world average annual wheat yield of 3.2 t/ha." This was based on five crops a year, each taking 70 days to mature.

If we pretend that wheat constitutes the entire diet of 2.57 kg/day per person and work with the measured figure of 700 tonnes per hectare—which is 70 kg/m^2 (a hectare is 100×100 meters)—then the annual food needs of that person would be met by 13.4 m^2. This will also provide heir oxygen.

For a crew of six we get 80.4 m^2. Stacked ten high, this would need a total floor space of 8m^2, and a volume of 80.4 m^3 (dwarf wheat needs a meter of headroom).

(Another NASA report says that a person needs 19 m^3 of living space to function optimally. That's 2.78×2.78×2.46 meters (9×9×8 feet). So that and the wheat would give a space requirement of about 200 m^3 for the crew of six.)

We now have an ecology of humans and wheat. There are evidently problems with this, apart from the nuisances of having only wheat to eat, and having to wait 70 days between harvests. Without solving all of these problems we can diversify the ecology somewhat.

First, if the wheat is grown hydroponically, we would have to supply all the nutrients in the right quantities, less what comes from human waste. As well as the carbon, oxygen and hydrogen that appear in the metabolic equations, plants need N (nitrogen), P (phosphorus), K (potassium), Ca (calcium), Mg (magnesium) and S (sulphur) in relatively large quantites (macronutrients), and Fe (iron), Mn (manganese), Zn (zinc), Cu (copper), B (boron) and Mo (molybdenum) in trace quantites (micronutrients).

We could add edible fish to the ecology and grow the wheat "aquaponically". Now our ecology has three species.

Or we could grow the wheat in soil. (We'd have to do that anyway if we wanted, say, apple trees on board: they would not stand up in a hydro- or aqua-ponic tank, unless we tried them in microgravity.)

This soil would be expensive to bring from Earth so we might have to make it from regolith, particularly if we're establishing a colony on the Moon or on Mars. Or from asteroids if we're making a habitat in space.

Lunar and Martian regoliths have some of the nutrients we listed, but often in unacceptable forms. For example, iron in the form FeO_2 is a nutrient, but in the forms FeO or just Fe will damage plants in the process of rusting.

In any case, to be used by plants, nutrients must be in soluble form. It takes certain microorganisms to convert insoluble nutrients. So now we have more species in our ecology. Soil, as well as containing decaying animal and plant matter, is itself an ecology. Here are some denizens.

Classification	Body width	Examples
Microflora	$< 10\mu$m	bacteria, fungi
Microfauna	< 0.1mm	protista, nematodes
Mesofauna	0.1–2.0mm	enchytraeids, mites, springtails
Macrofauna	> 2.0mm	earthworms, insects and larvae, slugs and snails

And, of course, some of these can be pathogens and pests. We will have to select knowing just about everything there is to know about species interactions.

Let's show that the Avalon habitat will support its proposed population of 10,000. The area of the cylindrical surface, which is at 1 gee, is

$$2\pi RL = 2\pi 530 \times 680 = 2264460 \text{ m}^2$$

and the area of its two end discs, which are proposed as greenhouses, is

$$2\pi R^2 = 2\pi 530 \times 530 = 1764947 \text{ m}^2$$

for a total of 4029407 m^2 or 403 m^2 per person. Plenty of room.

34. Population. Once we have a habitat in space, people will live there and do all the things that people do, some beneficial to the habitat, some detrimental.

One thing we must ask is: what about their descendents? If the habitat is a space colony within the Solar System, people will come and go, will return to Earth or colonize planets or build further space habitats. But if we put rockets on the habitat and send it to Proxima Centauri to investigate the Earth-like planet orbiting that red dwarf star 4.22 light years away, the habitat will have to be self-sufficient for generations.

Let's do the calculation. A light year is about 66 KAU (65,745 AU) where an Astronomical Unit, the radius of Earth's orbit, is 8 light minutes. A speed of 1 AU per year is about 4.56 Km/s, where kilometers per second are the convenient units to describe speeds of Solar System bodies and also of the fastest vehicles humans have made so far. Thus, NASA's Parker Solar Probe attained 200

Km/s or 0.067% of lightspeed c. Voyager 1, launched in 1978, is in 2021 152 AU from the Sun and travelling at 17 Km/s (3.7 AU/year, 0.0057%c).

So Voyager 1 would take 74 thousand years to reach Proxima Centauri, if it were going in that direction, and even Parker would need 6300 years.

The fusion-powered starship being imagined by Project Icarus wishes to reach the Proxima Centauri system in a century, i.e., travelling at 4%c.

So any human crew must be multi-generational.

This reveals some problems. The first is population control, essential in a finite environment.

To see what happens to a population with each couple producing a given number of children during the woman's fertility period of ages, say, 18 to 45, and people living so many years, probably requires a computer simulation. This gets complicated and hard to follow, so let's make a model.[3]

If each couple has three children at age 29 and then dies, we get a doubling time for the population of 50 years:

$$\left(\frac{3}{2}\right)^{50/29} = 2.0$$

Here the 3/2 specifies the replacement of the original couple (2 people) by the 3 children. The fraction $g = y/29$ gives the number of the generations of 29 years each that will be living after y years. In g generations the population will grow from an initial population of n_0 people to $n_0(3/2)^g$ people. That is, generation 0 will have n_0 people, generation 1 will have $(3/2)n_0$ people, generation 2 will have $(3/2)^2 n_0 = (9/4)n_0$ people, and so on: try it for $n_0 = 16$.

The particular numbers don't matter so much as that the population regularly doubles.

If we start the colony/crew with 49 couples (98 people) and allow a maximum capacity of 500 people, that capacity will be reached after

$$\lg\left(\frac{500}{98}\right) = 2.35$$

doublings. (The logarithm to base 2 is the operation that inverts taking powers of 2: $\lg(2^x) = x$ or $2^{\lg y} = y$, so $2^{2.35} = 500/98$. On your calculator you can find lg x by dividing log x/log 2.) That is $2.35 \times 29 = 68$ years.

Thereafter the colony or starship will be uninhabitable.

The overpopulation problem is easy enough to fix if we permit "social engineering": every couple is allowed only two children. (In fact they must each have at least two children or we reach the opposite extreme of underpopulation, to the extent of being unable to operate the ship or to found a colony at the end of the trip. Or there must be a complicated tradeoff among couples so that the *average* is 2 children each.)

Note that, with exactly two children per couple, we do not need to know the generation time of 29 years. The population is stable.

35. Genetics. The next problem is less easy to solve. What happens to the gene pool after so many generations?

Again, this is not such a big issue for a local space colony, which interacts with other populations, but it is serious for an isolated "world ship".

The problem is inbreeding. To discuss it we must gloss over much of the wonderful story of how our 30,000-odd genes describe 90,000 or so proteins which construct our cells; how the proteins

[3] A *model* is not a theory but a set of premises visibly oversimplified and in error; but which may cast some light on the modelled processes. A computer simulation is a less simplified model, but one whose understanding is correspondingly hard to communicate from the programmer to the reader.

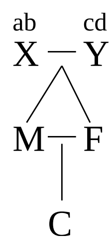
are intricately-folded chains of many amino acids selected from 20 types; how each amino acid is encoded by three letters of an alphabet of 4 different "letters", each being a two- or three-dimensional assembly of carbon, hydrogen, oxygen, nitrogen and other atoms; how these letters are written into our DNA, paired for redundancy, as rungs of its famous double helix; how the immensely long chains of DNA are coiled into chromosomes; and how in creatures including ourselves those chromosomes are paired, making us genetically *diploid* ("double") as opposed to haploid ("single").[4]

It is this latter pairing, not the "base pairs" in DNA, which is the mechanism for inheritance from our parents, and which can give rise to inbreeding in small populations such as our space crew.

The chromosome pairs occur in the nucleii of every cell in our body except the germ cells—eggs and sperm. There the diploid pairs have been separated, so the germ cells are haploid. When sperm and egg combine in sexual reproduction the chromosomes are paired up again, but in pieces containing individual genes. Thus the child inherits different variants of each gene, randomly, from mother or father.

The different variants of each gene are called *alleles*, for instance one for blue eyes and one for brown eyes, and there can be many alleles (green eyes, hazel eyes, etc.). We will suppose that our initial space crew has been selected so that all the alleles are different.

Now let's consider a classic example of inbreeding: brother and sister mate and produce a child.



I've shown the grandparents as X and Y and the paired alleles of one gene for each of them, a and b for X, and c and d for Y. The sibling parents are M and F and we'll have to work out all the possible combinations of the four alleles for each of them. Their (possibly inbred) child is C and we must work out all the further possible combinations of the four alleles for C.

For each of M and F the a, b, c, d of the grandparents can pair in eight possible ways.

ac	ca
ad	da
bc	cb
bd	db

The righthand column is just the mirror image of the lefthand column and so we don't need to consider it explicitly in the next step—as long as we don't forget it.

Since there are two parents, M and F, we must combine each of these eight with each of the same eight, giving 64 combinations (and we can reduce that to $4 \times 4 = 16$ explicit combinations). And each of the 64 produces a further 8 results, some of which will be duplicates: a final total of 512 possibilities for the child C.

Inbreeding causes both alleles in the child to be the same. So we must figure out the proportion of the 512 possibilities where that happens.

In combining each of ac, ad, bc, bd with each of ac, ad, bc, bd we will find three different patterns: two entries are the same; two entries share one allele; and two entries are completely different. You

[4]On the other hand, the DNA used to trace our ancestry comes from sources which are, effectively, not paired—the Y chromosome for male descent and the mitochondrial DNA for female descent—and so we speak of "haplotypes" and "haplogroups".

should try until you can see that these situations occur 4, 8 and 4 times respectively in the 4×4 combinations.

I'll give an example of each pattern. I won't include mirror images where they occur in the results, except that where the two alleles are the same I'll mark a 2 to show that the mirror image duplicates itself.

ac-ac		*ac-ad*		*ac-bd*
2*aa*		2*aa*		*ab*
ac		*ac*		*ad*
2*cc*		*ad*		*bc*
		cd		*cd*

Carefully adding all these up we get 128 cases where C's two alleles are the same. This is a quarter of the 512 total cases.

So the chance that C is inbred is 1/4 or 25%.

There is a rule of thumb for doing this calculation more quickly. It is called the *inbreeding coefficient* (or the coefficient of consanguinity).

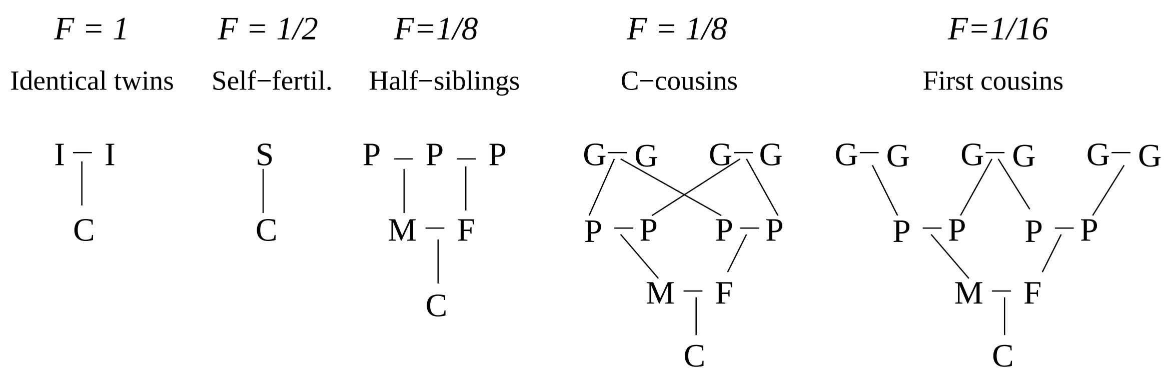
$$F = \text{ sum over all common ancestors of } \frac{1}{2^{p+m+1}}$$

where p is the distance from the father to the common ancestor and m is the distance from the mother to the common ancestor.

For the example of sibling parents $p = 1 = m$ and there are two common ancestors so

$$F = \frac{1}{2^3} + \frac{1}{2^3} = \frac{1}{4}$$

Here are some further examples, using F.



We can see that F is not always right, although the example showing error is an impossible one: identical twin parents should give the same result as self-fertilization. However, when the family tree is badly ingrown, F is hard to calculate and may not give the same results as working through all the allele combinations.

As an example of the harm inbreeding does we can look at Charles II of Spain (1661-1700) whose inbreeding coefficient was allegedly 0.254, who had difficulty eating and talking because of a deformed "Habsburg jaw", who was hydrocephalic and who did (could?) not reproduce. Reproduction problems are among the many associated with inbreeding, and would spell disaster for our interstellar voyage.

The possibility of inbreeding is increased by *genetic drift*, which is particularly damaging in small populations. The probabilities above apply if everyone in the population produces children, but that is not always the case. If some individuals don't breed, their alleles could be reduced in the population and a few slanted such mishaps could eliminate the allele altogether.

In populations which are not isolated, drift can be mitigated by migration, in which individuals from other populations restore alleles or add new ones. That would apply to a local space colony but not to a starship—unless the ship were part of a fleet.

Mutation is another mitigating factor. Alleles change in individuals, most often by copying errors but also by causes in the environment such as ultraviolet light, chemicals or viruses. In humans there are 50 to 90 new mutations per generation. This is a small percentage of our 30,000 genes (1 in every 600 to 333) but amounts to 42% to 75% changeover in the 250 generations represented by 6300 years of travel. Most mutations, unfortunately, are not beneficial.

It may be best to seek a totally new solution. We do not know yet, however, how to suspend animation and induce hibernation in the human body, so the initial crew merely sleeps out the journey. But some animals do it (for much shorter periods) and we can learn from them.

We also do not know how to freeze human embryos or whether a first generation at the distant exoplanet could be raised successfully by robots sent to accompany them.

An intermediate solution might be to keep the multigeneration, active crew, but reproduce by *cloning* for the duration of the voyage. This would keep the original, selected genetic population unaltered, apart from mutations. The social engineering would be, perhaps, less drastic than that needed to preserve the genetics with normal reproduction: the husbands would be sterilized and the wives each carry and give birth to two clones, hers and her husband's. There might even be some cultural resistance, at the end of the trip and the founding of the colony, to going back to sexual reproduction.

36. History. There can be no history on a starship. An insurrection or even a renegade is too dangerous for the limited space and fragile support systems. A challenge even to ideology risks the vision, which must be constant: "we're going to Proxima Centauri!".

Human enterprises don't remain in the family for more than a couple of generations. Even dynasties peter out. The only organizations that have survived millennia are religions. So the objective of the starship is going to have to be akin to a religion.

It must be stable but not static. And it cannot be repressive or it will face insurrection and renegades.

This, I think, is the greatest challenge to multigenerational travel, well beyond the other difficulties we've looked at.

I wonder if the cloning solution to the genetics problems of the previous Note will help here too. You inherit all the aptitudes of your progenitor, making it perhaps easier to impart also motivations and skills.

Of course, a catastophe is a historical event and starship society must be flexible enough to recover. If you hit a patch of antimatter—just to introduce a situation which may not have been anticipated—and seriously damage the ship and lose some crew, you must be able to repair the damage and replace the genes and skills.

And I am assuming that the crew are indeed crew, with responsibilities for running the ship, and not just passengers who will only build the colony at the end. I don't see a passive society as being anything but dangerous.

I can't be quantitative about history. If there is no history there is perhaps no need to be quantitative: science uses quantities to refine inference, but if there is no change then there is nothing to predict. (Not that history is predictable—it is too chaotic—but there is such a thing as historical inference.)

37. Self-reproducing probes. If it is too challenging to send people to the stars, maybe we can

send machines, at least to start with.

A probe could study the star and its environment, especially its planets, and report back. It could even stay awhile and monitor for the emergence of life, or, if life, the emergence of intelligence, or, if intelligence, for its attitudes towards neighbours such as us.

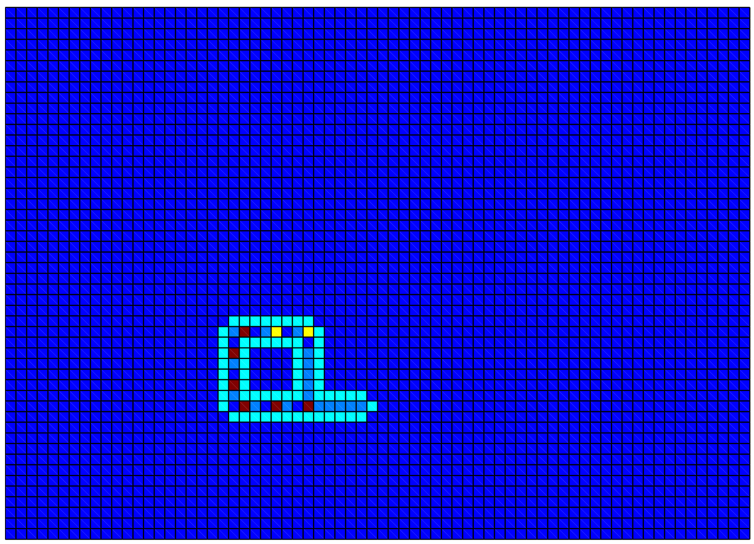
This would require some smart probe, but maybe our AI (artificial intelligence) will soon be up for it.

It would be expensive to send probes from here to all 100 billion stars in the galaxy, or even to all star systems with inhabitable planets. But maybe the probes can send out further probes.

This would require a self-reproducing machine—a probe which can make another probe like itself. Is this possible?

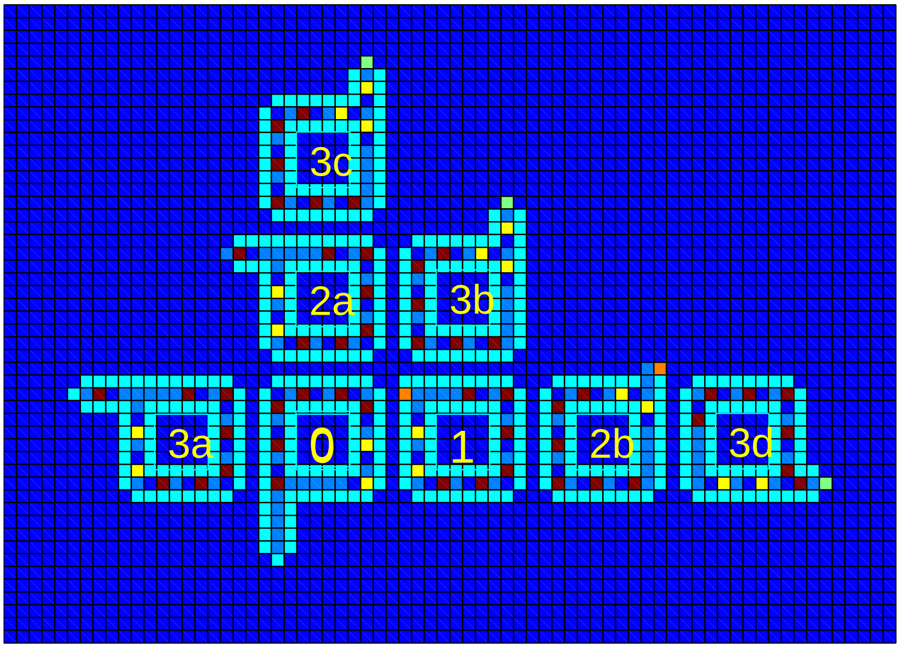
Here is a self-reproducing machine.

Time 0



And here it has reproduced to three more generations. (The labels 0, 1, 2a, etc. are not part of the machines but have been added by hand.)

Time 441



You can see the original "machine", labelled "0", in an exact repetition of its original state, albeit rotated 270 degrees counterclockwise (90 degrees clockwise), and ready to reproduce again.

Meanwhile, it has already reproduced three times, generating individuals "1", "2a" and "3a", next to itself, basically turning 90 degrees each time.

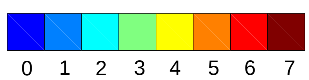
The sole individual of the first generation of offspring, "1", also reproduced ("2b" and "3b") before becoming quiescent because it had no room to produce a third offspring. (It's a machine: it doesn't realize it could skip a turn and reproduce downwards.)

The individuals of the second generation have each reproduced once ("2a" to "3c" and "2b" to "3d") and have room to reproduce once more each before going quiescent.

Notice that the number of descendents grows exponentially: 1 in the 1st generation, 2 in the 2nd and $2^2 = 4$ in the 3rd. But, because of crowding, this does not continue. You can check that subsequent generations will have 7, 10 and 13 individuals, rather than 8, 16 and 32.

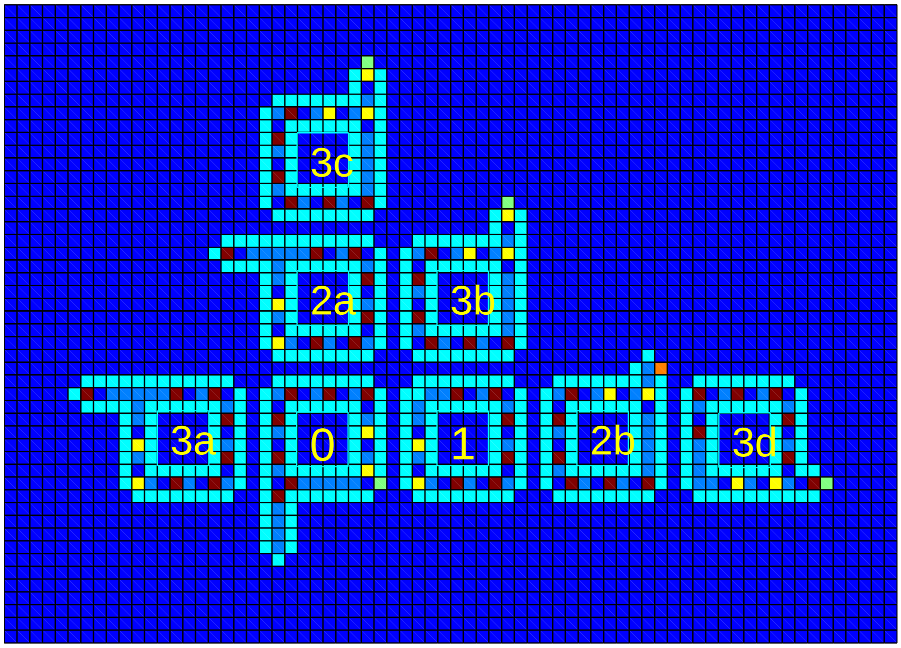
The picture looks like a systematic way to explore a 2-dimensional galaxy. Just consider adjacent locations to be neighbouring stars and reproduction to include the interstellar voyage from star to neighbour.

How does this reproduction work? Well, the colours are just to make it more appealing. They actually are numbers.



The changes from one time to another, such as from time 441 to time 442

Time 442



are given by *transitions* such as

$$\begin{array}{cccl} & 0 & & \\ 2 & 7 & 1 & \rightarrow 0 \\ & 1 & & \end{array}$$

and

$$\begin{array}{cccl} & 2 & & \\ 7 & 1 & 1 & \rightarrow 7 \\ & 2 & & \end{array}$$

and

$$\begin{array}{cccl} & 7 & & \\ 2 & 1 & 2 & \rightarrow 7 \\ & 1 & & \end{array}$$

Can you spot these in individual “0”?

Indeed, the third transition above is a rotation, 90 degrees clockwise, of the one before it. Since the individual machines take up orientations which step 90 degrees from each other, any transition allowed entails its 90, 180 and 270-degree rotations as well.

(Each transition also entails its reflection, except for the one that is responsible for generating the left-hand turns.)

You can detect some patterns. Cells in state “1” resemble nerves conducting signals, and cells in state “2” form the nerve sheath. Together they make “data lines”.

Cells in state “7” are signals which propagate along a nerve and copy themselves when they come to a T-junction. (That copying is the gist of the three transitions I gave explicitly above.) The combination "70" gives the direction of propagation, which is from "0" towards "7".

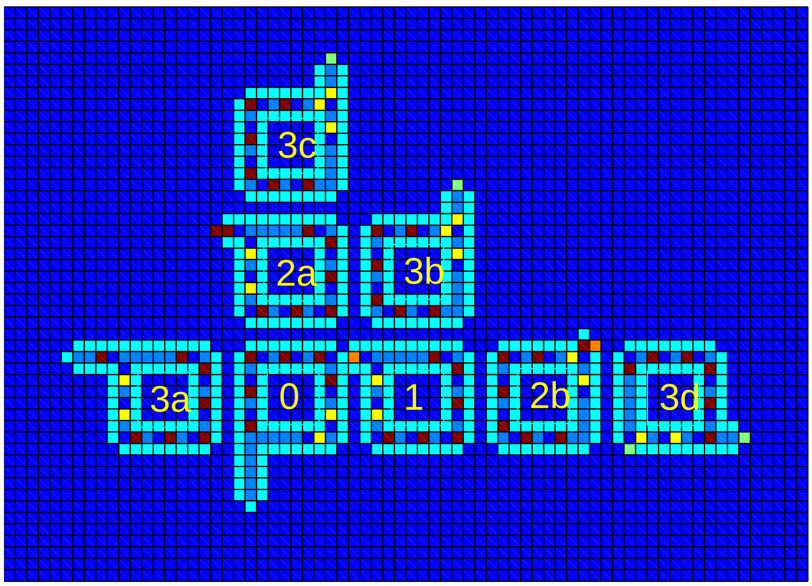
When a "7" reaches the end of a nerve, it extends it.

"40" signals propagate and duplicate in the same way, and a pair of them serves to extend the nerve with a left turn. ("3" cells help with this. They are a little hard to spot, being almost the same colour as sheath cells, and, indeed, no left turn is happening or about to happen in the two time steps I've shown above.)

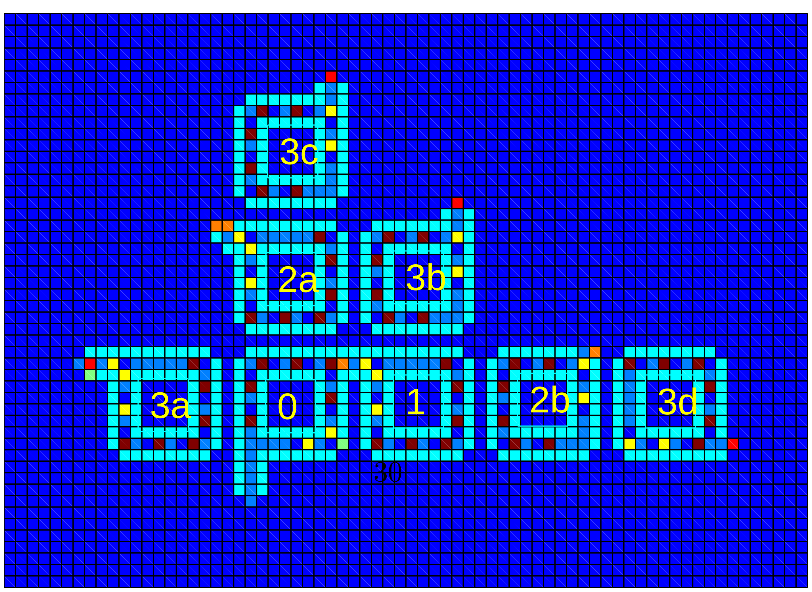
Cell states "5" and "6" perform different tasks depending on context. They respectively cut the "umbilical cord" between parent and child, and start the extension that makes the child's "constructor arm" (which eventually becomes an umbilical cord).

You can see "5" in a couple of other roles in time 441. To see "6" we must go back to time 439. So I've included time 440 for an unbroken sequence.

Time 440



Time 439



I have not shown details of data line extension or left turns, or of severing a completed child from the parent. These are found in the reference in the Excursions.

I do begin to show, in these four time steps, the "dying" of an organism when it is too crowded to reproduce. Time 442 shows the begining of the end for organism "1". The new sheath-state cell blocking the circulation of the data line remains there indefinitely, and effectively converts each "70" and each "40" signal into "11" nerve cores. So by time 467 no signals are left circulating in organism "1". It has become inert, and serves basically as structure for living cells to build upon, rather like dead coral at the centre of a reef.

For a self-reproducing probe, such quiescence would indicate an end of reproduction but not of monitoring and communication. The latter could go on indefinitely (if we could make the probe effectively immortal).

If each probe produced two offspring then 27 generations[5] could investigate $2^{27} \approx 100$ billion stars, all the stars in the Milky Way galaxy. If the probes can travel at 1% lightspeed, they will each need 500 years to travel the 5 light years that is the average distance between stars in the galaxy. Reproduction time should be small compared to this. So the probes can colonize the galaxy in $27 \times 500 = 13,500$ years. This is a very short time.

38. "Where Are They?" If we can send out probes to monitor the galaxy, so can alien civilizations. The Milky Way is three times the age of the Earth (13.5 versus 4.5 billion years). So there can have been a lot of technological civilizations that predate us. And there has been a lot of time for their probes to reach us. But we haven't encountered any.

Considerations such as this led Enrico Fermi to pose his famous paradox, as the question "so where are they?".

Self-reproducing probes are not yet proven technology. But radio astronomy is, and in 1961 a small meeting was held to discuss listening for extraterrestrial signals. So SETI was born: the search for extraterrestrial intelligence.

At that meeting, to focus discussion, Frank Drake presented an equation which formalizes our ignorance of N, the number of detectable civilizations in the Milky Way.

$$N = R_* \times f_p \times n_e \times f_\ell \times f_i \times f_c \times L$$

Here the R is a rate (number per year), the fs are fractions, the n is a number, and the L is a time (years), making N a number times a number, which we take to be a number. The terms build on each other, as follows.

- R_* the rate of formation of stars in the galaxy.
- f_p the fraction of those stars with planetary systems.
- n_e the average number of planets, per star that has planets, that can potentially support life.
- f_ℓ the fraction of such planets on which life actually appears.
- f_i the fraction of life-bearing planets on which intelligent life emerges.
- f_c the fraction of civilizations that develop a technology which produces detectable signs of their existence.
- L the average length of time such civilizations produce such signs.

[5] Actually 26, saving 500 years, because all generations are colonizing star systems, not just the 27th.

Note that we don't have values for any of these terms, except possibly R_* and, in the last decade or so, but long postdating the 1961 meeting, f_p.

The Drake equation cannot lead us to any conclusion, but since it focusses what we do not know, it is useful in directing research.

But since the number of habitable planets in the galaxy, $100\mathrm{G}\times f_j \times n_e$, now appears pretty close to the number, 100G, of stars, the other terms are going to have to be microscopic to leave us alone as the only galactic civilization capable of sending radio signals (or interstellar probes, or detectably changing the composition of our atmosphere). ("Intelligence" could be defined as any one of these capabilities.)

But no signals have been detected. In sixty years. How likely is that?

Let's reverse the picture and put ourselves in the position of *sending* a message. In fact, we've already done that more than once. In 1974 a 450 kilowatt transmitter at the Arecibo 305-meter diameter radio telescope beamed a 3-minute message towards the M13 globular cluster neighbouring our galaxy at 25K light years.

How strong will that signal be when it reaches M13 25 thousand years from now?

The effect of an antenna—and the Arecibo dish was serving exactly as an antenna for this signal—is to focus the signal so that instead of spreading uniformly in all directions ("isotropically") it is vastly reinforced in one particular direction (or possibly in a limited number of directions).

The *gain* of a circular parabolic dish is how much it multiplies the signal in the desired direction, and is approximately

$$5.18\left(\frac{D}{\lambda}\right)^2 = 5.18\left(\frac{305}{0.126}\right)^2 = 30_{10}6$$

where D is the 305-meter diameter of the dish and $\lambda = c/f$ is the wavelength of the $f = 2.38$ GHz signal, which can be found by dividing light speed $c = 0.3$ Gm/s by the frequency f to get 126 mm.

Multiplying the 450 KW of the transmitter by this gain gives a power towards the target of the equivalent of 14 terawatts if the signal were radiated equally in all directions.

A signal which travels in all directions for 25 thousand light years, or $25_{10}3\times0.3_{10}9\times365\times24\times3600 = 25_{10}3\times9.5_{10}15 = 2.4_{10}20$ meters, will spread equally over the surface $4\pi r^2$ of a sphere of that radius r. That is the 14 terawatts will be attenuated to

$$\frac{14_{10}12}{4\pi(2.4_{10}20)^2} = 2.0_{10}\text{–}29 \ \ \text{watts/m}^2$$

This is a pretty weak signal. Can ET detect it?

What is the energy of a photon? Yes, radio waves, being part of the electromagnetic spectrum, like light, are photons, too, of energy

$$hf = 6.626_{10}\text{–}34 \times 2.38_{10}9 = 1.58_{10}\text{–}24 \ \ \text{joules}$$

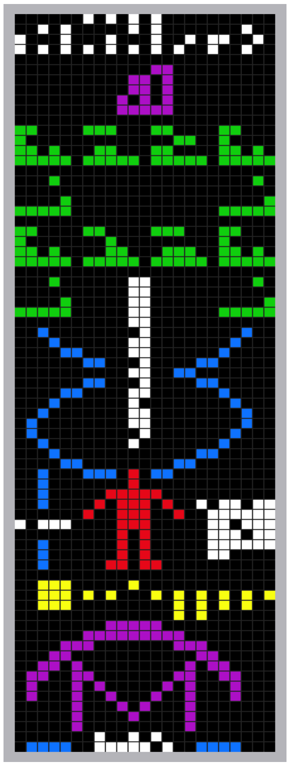
where h is *Planck's constant* in joule-seconds.

A photon per second would deliver this same number of watts.

Spreading that wattage over an area of 79K meters squared is the 2.0_{10}-29 watts/m^2 ET is receiving at M13. A 160-meter dish will suffice, if ET's radio receiver can detect one photon per second.

Of course, that is only to *detect* our signal, not to read it. That calculation brings us into the realm of radio sensitivity which involves not only watts/m^2 but also bandwidth of the signal (the Arecibo message at 10 bits per second required a bandwith of at least that many hertz) and the temperature of the whole receiving system (because temperature amounts to noise and the signal-to-noise ratio must be large enough to distinguish the 0- from the 1-bits).

Since I've introduced the Arecibo message, here it is.
(Source: https://en.wikipedia.org/wiki/Arecibo_message last accessed 2024 Sep 15.)



Numbers 1 to 10 in binary

DNA chemical elements: H(1) C(6) N(7) O(8) P(15)

DNA nucleotide compounds, e.g., deoxyribose 7H 5C 1O
adenine 4H 5C 5N thymine 5H 5C 2N 2O
phosphate 4O 2P
cytosine 4H 4C 3N 1O guanine 4H 5C 5N 1O
phosphate 4O 2P

DNA helix ~2^32 nucleotides DNA helix

14x126mm human ~4G people

Solar system, Earth highlighted

Arecibo

2430x126mm

See if you can decipher it from the clues. Note that the signal was 1679 bits which is the product of primes 73 and 23: ET is expected to figure out from that that the message is 2-dimensional before starting to decipher it. Colours are not in the message but will help you: blue, red, yellow and the bottom purple are drawings; the rest are binary numbers, mostly vertical, sometimes horizontal.

M13 is outside our galaxy but some stars in our galaxy are three times further away: the diameter of the Milky Way is 100K light years and we are 26K lightyears from the centre. So the Arecibo message, if sent across the galaxy, would arrive at 1/9th the above strength, and require a dish 3 times bigger to pick it up. That is 480 meters, just under the size of FAST, the Five hundred meter Aperture Spherical radio Telescope in China's Guizhou province.

So in principle we can communicate across the galaxy, and ET anywhere in the galaxy can communicate with us. Maybe almost with our present technology. But ET would have to be willing to transmit, and able to transmit continuously in all directions at those terawatts of power. And we would have to listen in all directions, if not at once then at least during ET's transmission.

We haven't achieved that isotropic listening yet, so it may not be surprising that we've heard nothing in sixty years.

And then there is ET's willingness to transmit. Are *we* willing to transmit? We have let out a few bleats but we don't know what's out there. Maybe we need an informed public debate, since contact, especially with an ET older and superior to us, will affect us all. Even if ET does nothing but talk, will knowing of capabilities (far) beyond our own inspire us or diminish us?

Part IV Spaceship Earth.

39. Speeds.

II. The Excursions

You've seen lots of ideas. Now *do* something with them!

1. The data for the graphs in Note 28 come from [Ros13] for world GDP, [Rit14] for world and U.S. energy, and https://www.thebalance.com/us-gdp-by-year-3305543 for U.S. GDP. Forecasts of this sort were pioneered by [Mas17].

2. The Avalon space colony of Notes 28, 29, 30 and 33 is described in overview by [GS19].

3. The two papers I worked from for Note 30 on radiation were [SN91] and [CKC12]. Both are from NASA Langley Research. The first (the earlier one) gives detailed analyses of a Mars-bound spacecraft and of two martian habitats.

4. Two references for Note 31 on space debris are [Pag20] (tractor swarms) and [Rey87] (boids).

5. A good start on the space elevator of Note 32 is in [Arv07]. In addition the June/July 2016 issue of the Journal of the British Interplanetary Society (JBIS vol.69 nos.6/7) is dedicated to space elevators.

6. Calculate the equivalents of r_E, r_G and r_A, and the tensile strength needed for a space elevator on Mars. What about Luna? Note that the lunar L1 Lagrange point, 59 Mm from the Moon and 326 Mm from Earth, is "lunasynchronous" (as is Earth itself, or anywhere on the line between their centres) and could provide an anchor.

7. As well as NASA and Wikipedia documents online, I've used three articles in Note 33 on ecology: Wheeler [Whe10] on plants for human life support, Asseng et al. [Ass20] on wheat yield, and Soilleux [Soi21] on soil from regolith.
   A more detailed discussion, by contrast, comes up with 900 m^2 per person [MBTG18], with the 30-fold increase mainly due to adding variety into the diet, particularly animal protein..

8. The paper just cited by Marin and colleagues cites predecessor papers which I consulted for Notes 34 and 35.

9. The self-reproducing machine of Note 37 is called a Langton loop, named after Chris Langton [Lan84] who simplified the work of Ted Codd who in turn simplified the original work of John von Neumann. Self-reproducing probes are often called von Neumann probes.
   The two-dimensional transitions are the basis for *cellular automata* invented by Stanislaw Ulam and exploited by von Neumann. Langton loops use a "neighbourhood" of five (the term includes the cell being updated itself: the "neighbours" are all the cells that affect its next state) and eight states per cell. (Like Codd; von Neumann used 29 states. Both Codd and von Neumann automata are too complex ever to have been simulated.)
   We can think of the transition rules as "laws of nature" and the Langton loop as a particular organism tuned to exploit them for self-reproduction. Langton published his 219 transitions in the above citation. A program to use them must also check for rotations and reflections. (In one case, for that left turn, the transition table overrides the need to check reflections.)
   I spent several days tinkering with Langton's "laws of nature", unnecessarily but instructively.

(Apart from "I"s, which should be "1"s, as targets for half a dozen transition rules, Langton's transition table works perfectly once the program to execute it is free of bugs.) What was instructive was the number of ways an organism can go wrong and die spectacularly. I came away with deepened respect for evolution, which does this sort of tinkering randomly without even trying to think it through. Forms of artificial life such as this give a wonderful introductory appreciation of biology.
A search for Langton's loops gives a Wikipedia page describing further simplifications, which are too simple to seem interesting, and elaborations to include evolution or sexual reproduction instead of Langton's cloning. It also leads to a Mathematica simulation by Wolfram which will let you follow the Loops step by step. (But I prefer my MATLAB simulation.)

10. Elaborating on part of the previous Excursion, the following picture gives a simple introduction to rotation and reflection as permutations of 2, 3 and 4 symbols. The latter takes care of the non-self "neighbours" of a 5-neighbour cellular automaton such as Langton's.

a b	a b c	a c b	c a b	a b c d	a b d c	a d b c	d a b c
b a	b a c	b c a	c b a	b c a d	b c d a	b d c a	d b c a
				c a b d	c a d b	c d a b	d c a b
				b a c d	b a d c	b d a c	d b a c
				a c b d	a c d b	a d c b	d a c b
				c b a d	c b d a	c d b a	d c b a

The identity permutations are in black, the rotations in red, and the reflections in blue. Purple is both. The remaining colour gives permutations that are none of the above.
(All permutations of four symbols can be considered rotations or reflections if the symbols are vertices of a tetrahedron—in 3D.)
How many of each category are there in all? Can you extend the picture to five symbols?
Note that if two or more of the symbols represent the same thing, e.g., if *abcd* means 1123, some of the permutations will be redundant. How many?

11. If each probe in Note 37 produced ten offspring, how many generations would be needed to cover the galaxy?

12. A more detailed analysis than in Note 38 of signal strengths needed for interstellar communication is given by [BB14] in a special issue dedicated to the "METI debate" (*messaging* extraterrestrial intelligence). This particular analysis argues that all our radio emissions so far, including the Arecibo message, its successors, and the strong radar pulses we occasionally send at near-Earth asteroids to see if they are still safe, have been scarcely detectable—so there is still time to debate whether we should become a little quieter. Other discussion (not in that issue) argues that METI should be limited to the solar system and those places in it (Lagrange points, some satellites and asteroids) where ET might have placed probes because they already know about us from other monitoring. What do you think?

13. Any part of the Preliminary Notes that needs working through.

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